

(A few) Open issues at RHIC

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- why spacetime dynamics is important
- opacity at RHIC
- heavy quarks
- origin of high-pT particles

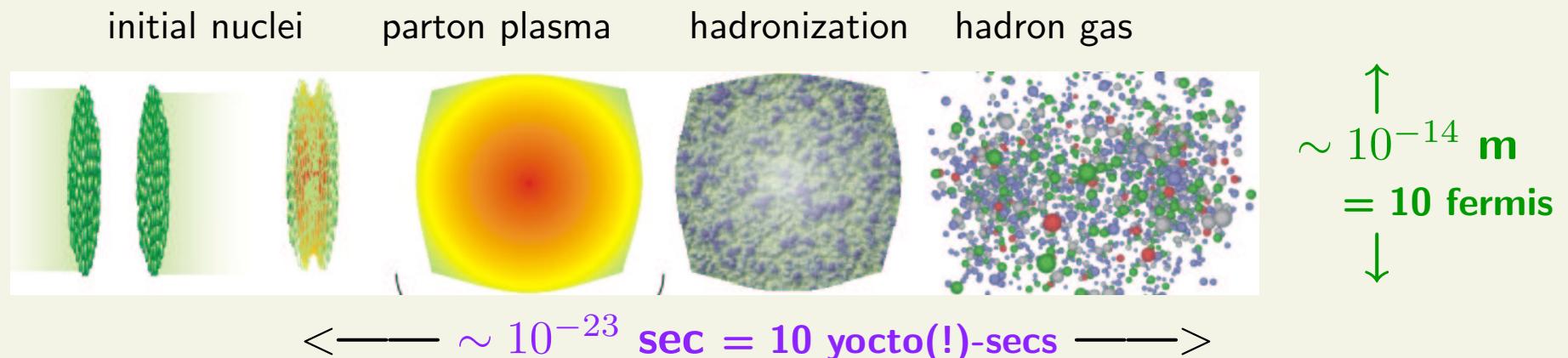
Heavy-ion physics

- partonic condensed matter physics Kajantie '96

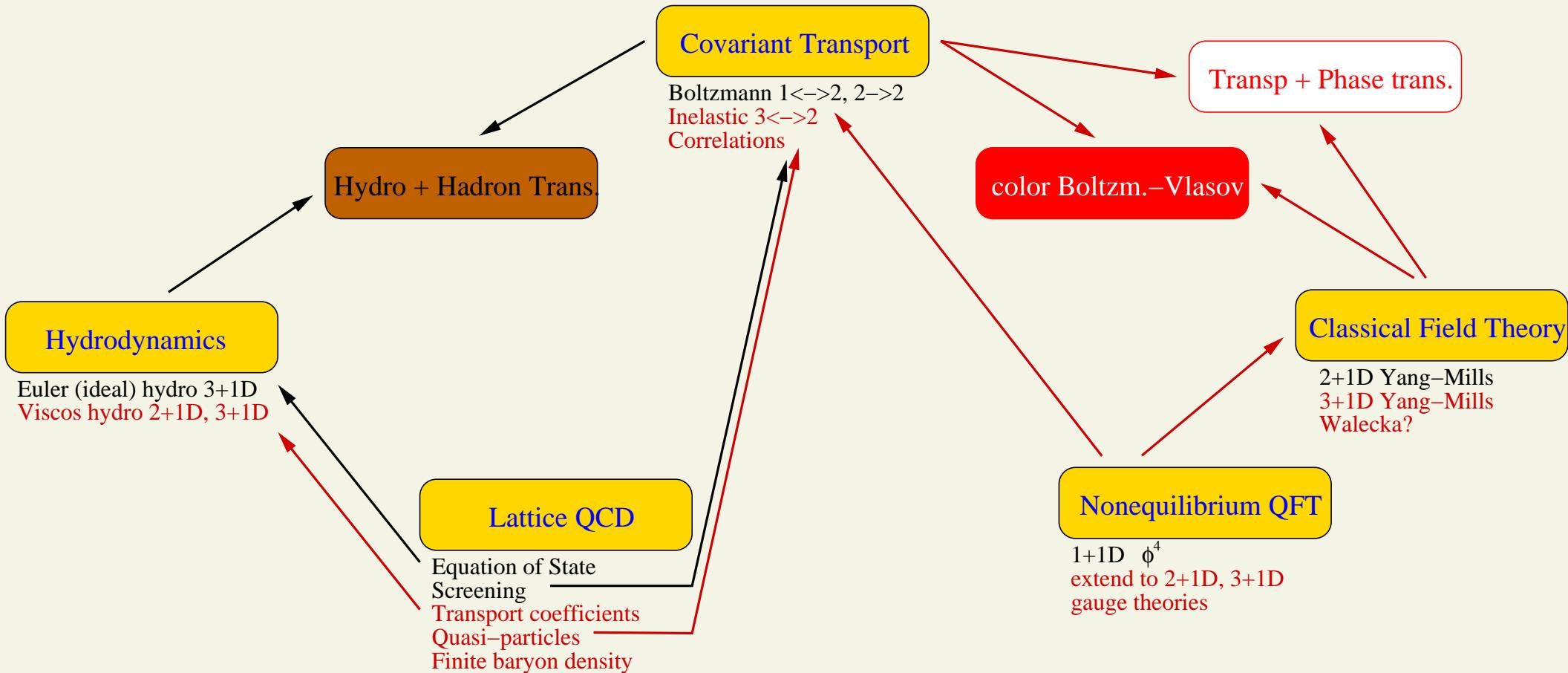
many-body system $\gg \sum$ constituents

- collision dynamics (\sim plasma physics, nonlinear systems)

evolving system \gg system in a box



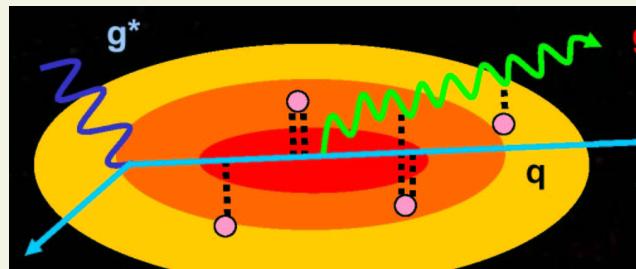
Dynamical frameworks



lots of progress - but still a long way to go

Dynamics matters even for high pT

parton energy loss → color charge density Wang, Gyulassy, Vitev, Wiedemann et al



static Yukawa scattering centers (GLV approach)

$$V(q) \propto e^{-i\vec{x}\vec{q}} \delta(q^0) \frac{\alpha_s}{\vec{q}^2 + \mu_D^2} T_a^{jet} \times T_a^{center}$$

$$\sigma_{tot} \sim \alpha_s^2 / \mu_D^2, \quad \langle \Delta q^2 \rangle \sim \mu_D^2$$

radiative parton energy loss can be computed perturbatively, if location of scattering centers known

⇒ needs input: space-time evolution of medium

e.g., GLV “pocket” formula:

$$\Delta E^{(1)} \approx const \times \alpha_s^3 \int \underbrace{dz}_{\text{gluon self-coupling (non-Abelian theory)}} \cdot \underbrace{z}_{\text{(non-Abelian theory)}} \cdot \rho(z, t = z/v) \quad dE/dx \propto x(!)$$

gluon self-coupling (non-Abelian theory)

main GLV result, from pion R_{AA} at RHIC: $dN_{glue}(b = 0)/d\eta \sim 1100$

in “agreement” with ideal hydro & data: $dN_{hadrons}(b = 0)/d\eta \sim 1100$

is there really so good an agreement?

GLV systematic error - highlights:

- **static scatterers (Coulomb, $V(\vec{q})$)** → Wiedemann, Salgado, try adding “flow”
- **simplified multiple gluon radiation (Poisson, from QED)**
- **Eikonal (high-energy) approximation**
- **pocket formula $\sim 10 - 20\%$ accurate (approx. average over scatt. centers)**
- **applications assume thermalized system** - $\mu_D \sim gT$, $n \sim T^3$

where are the quarks? - make up roughly half of QGP (in equil.)

effective quench factor relative to pure glue:

$$c_{eff} \equiv 1_{gluon} \times x_{gluon} + \frac{4}{9}_{quark} \times (1 - x_{gluon}) = \frac{16 + \frac{14}{3}N_f}{16 + \frac{21}{2}N_f} < 1$$

i.e., $dN^{pure\ glue}/d\eta \sim 1100 \Leftrightarrow dN^{QGP}/d\eta \sim 1600 - 1750(!) \quad (N_f = 2-3)$

\Rightarrow **ENTROPY problem** - $dN_{hadrons}/d\eta < dN_{partons}/d\eta \dots ?$

could argue initially mostly gluons - but quark equilibration dynamics cannot be ignored DM '04

quenching depends on full time history $\int d\tau \tau n_{eff}(\tau) \sim \int d\tau n_0 c_{eff}(\tau)$

+ then also need hydro with QGP out of chemical equilibrium...

ideal hydrodynamics systematic errors:

- **assumes local thermal equilibrium**
→ nonequil. studies Zhang, Gyulassy, DM, Greiner, Xu ...
- **no dissipation (zero viscosity)** → dissipative studies Gyulassy, Zhang, Teaney, Muronga...
- **violates quantum mechanics** $\Delta E \Delta t \geq \hbar/2$
- **sudden freezeout (Cooper-Frye, hypersurface)** → **need hadron transport**
Dumitru et al, Teaney et al, Nara et al

estimate effect of “minimal” viscosity $\eta/s \equiv \kappa = 1/(4\pi)$: DM '05

for 1D Bjorken expansion, ideal gas $\epsilon = 3p \propto T^4$, $\partial_z u_z \neq 0$

$$\frac{d\epsilon}{d\tau} + \frac{\epsilon + p}{\tau} = \frac{4}{3} \frac{\eta}{\tau^2} \approx \frac{4}{3} \kappa \frac{\epsilon + p}{T\tau^2}$$

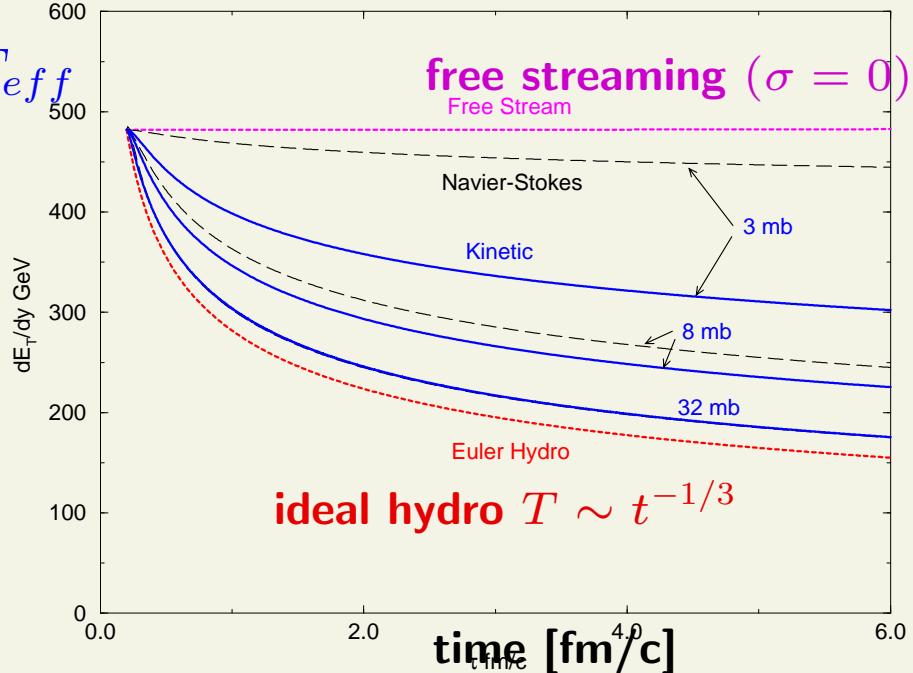
$$\Rightarrow \frac{T(\tau)}{T_0} = \left(\frac{\tau_0}{\tau} \right)^{1/3} \left[1 + \frac{2\kappa}{3\tau_0 T_0} \left(1 - \left(\frac{\tau_0}{\tau} \right)^{2/3} \right) \right]$$

entropy production already relevant during QGP phase at RHIC

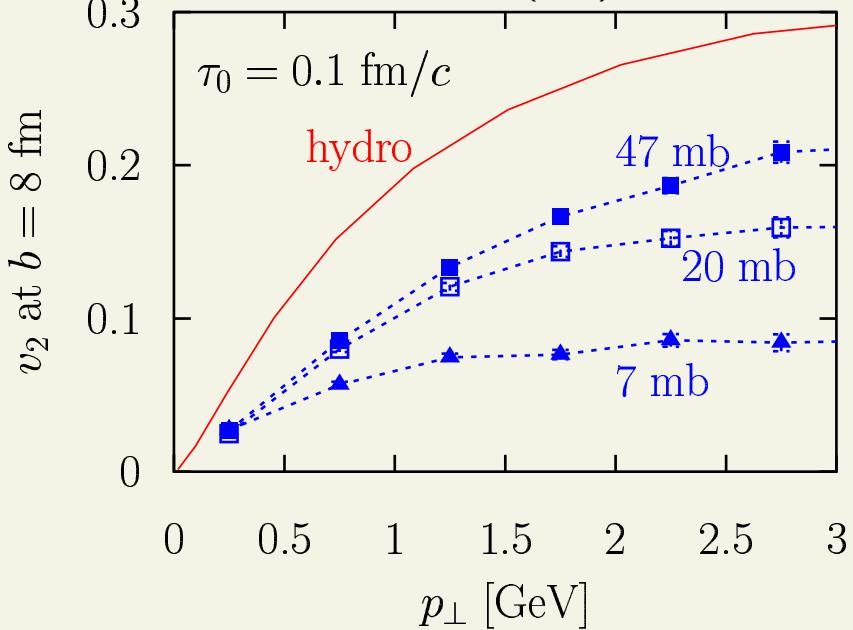
$$\frac{\tau s}{\tau_0 s_0} = \frac{\tau T^3}{\tau_0 T_0^3} \approx 1.1 - 1.2$$

$(\tau_0 = 0.6 \text{ fm}/c, T_0 \sim 300 \text{ MeV}, \tau_{QGP} \sim 3 - 5 \text{ fm}/c, \kappa = 1/4\pi)$

Gyulassy, Pang, Zhang ('97): 1+1D kinetic

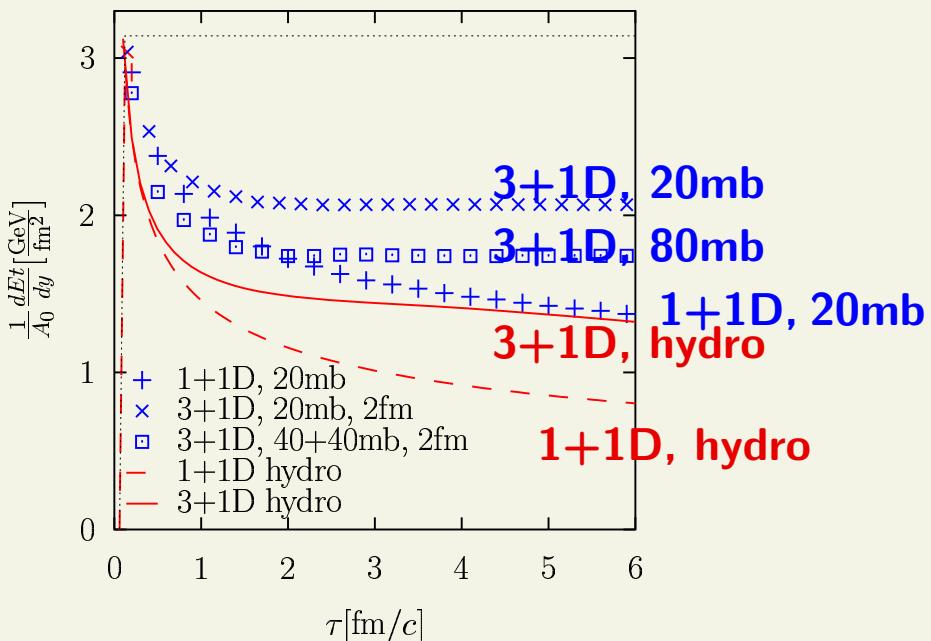


DM & Huovinen, PRL94 ('05): $\lambda \approx 0.1$ fm

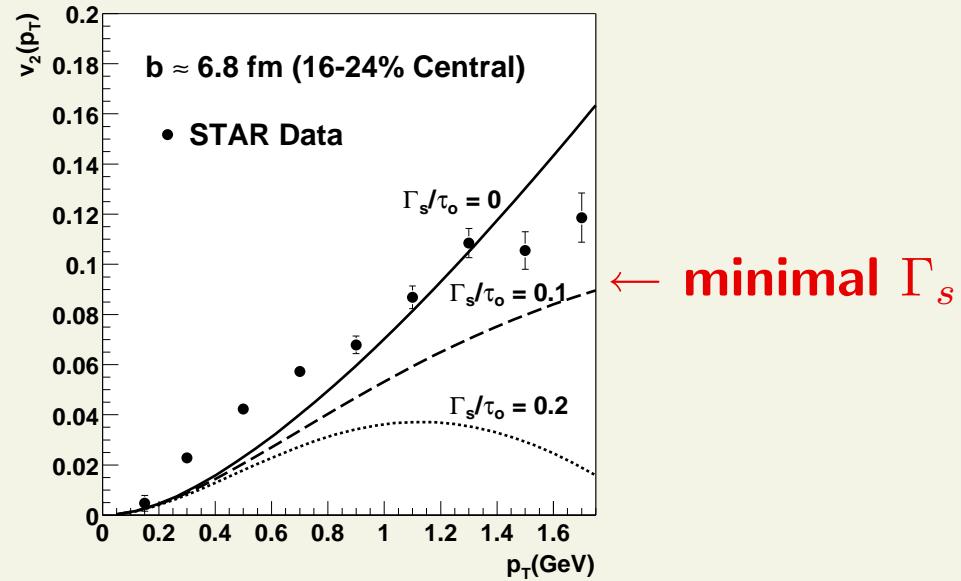


DM & Gyulassy ('00): 3+1D kinetic theory

MPC vs hydro (1+1D and 3+1D)



Teaney ('04): $\Gamma_s \equiv 4\kappa/3T$



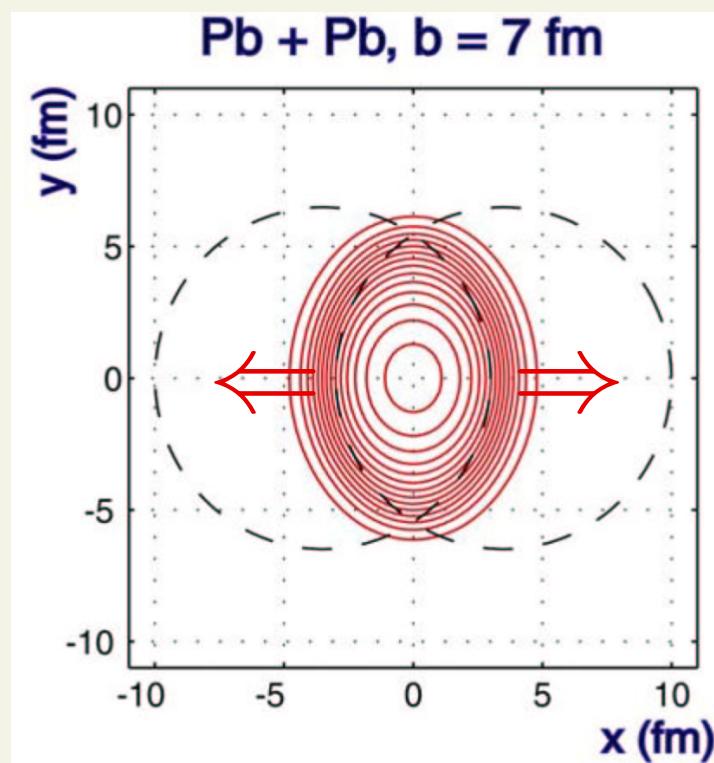
Opacity at RHIC

- **how can we measure/extract it?**
- **what is the dominant mechanism? - elastic, inelastic processes**
- **what is the length dependence?
incoherent “ $\propto L$ ”, LPM interference “ $\propto L^2$ ”**

One measure - elliptic flow

macroscopically: pressure gradients

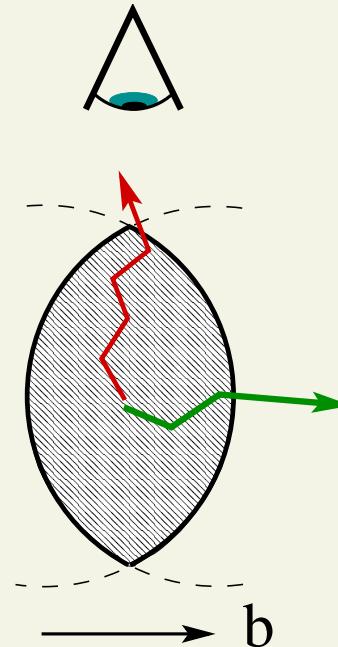
$$\Delta \vec{F}/\Delta V = -\vec{\nabla}p$$



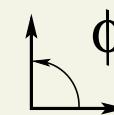
⇒ larger acceleration in impact parameter direction

microscopically: transport opacity

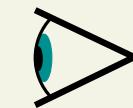
smaller momenta
more deflection



beam axis view

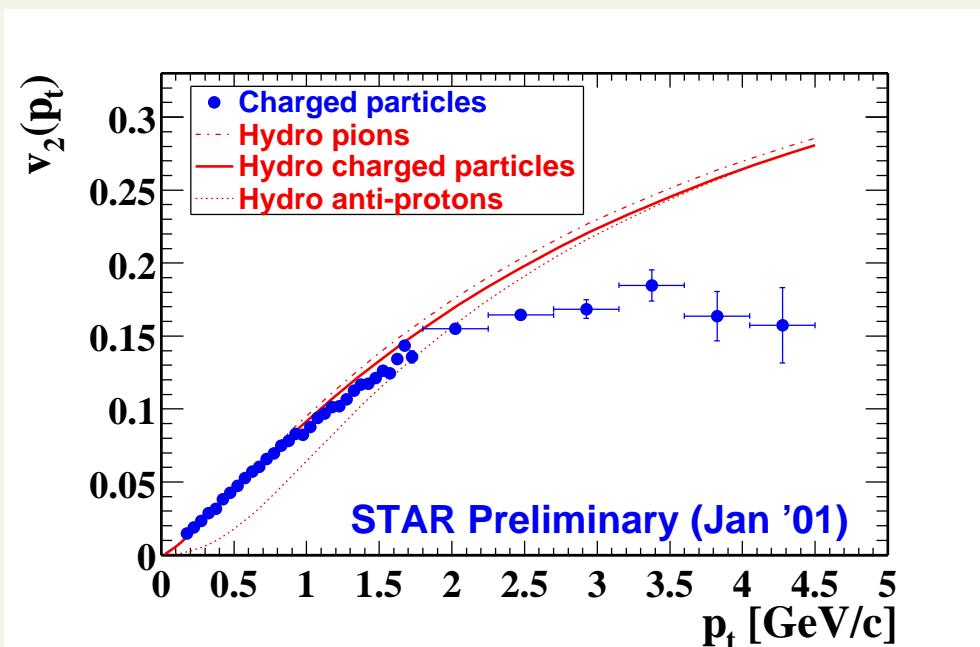


larger
momenta
less
deflection

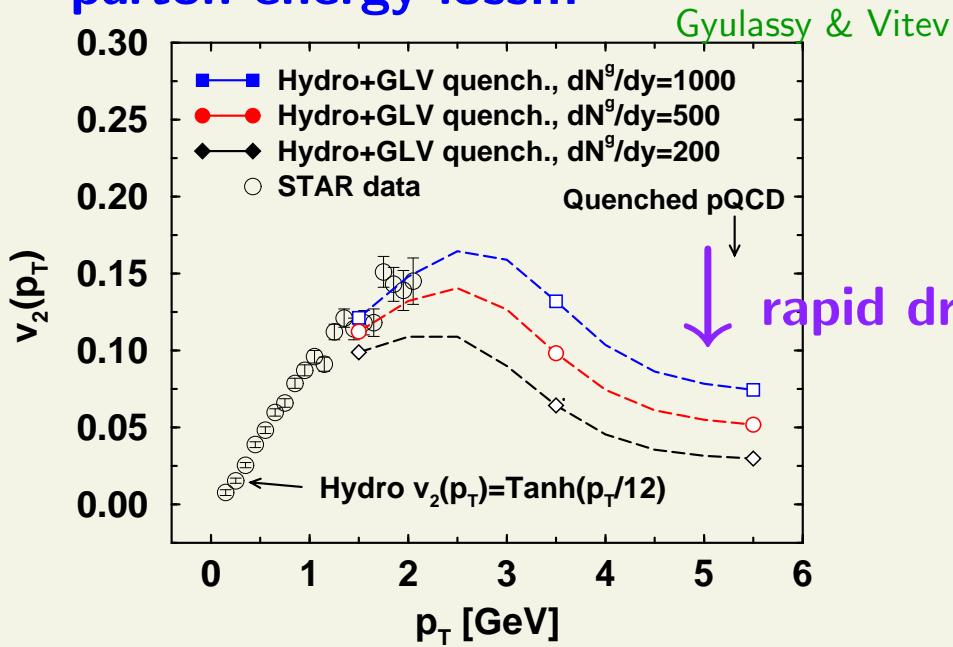


variation in pathlength
⇒ momentum anisotropy v_2

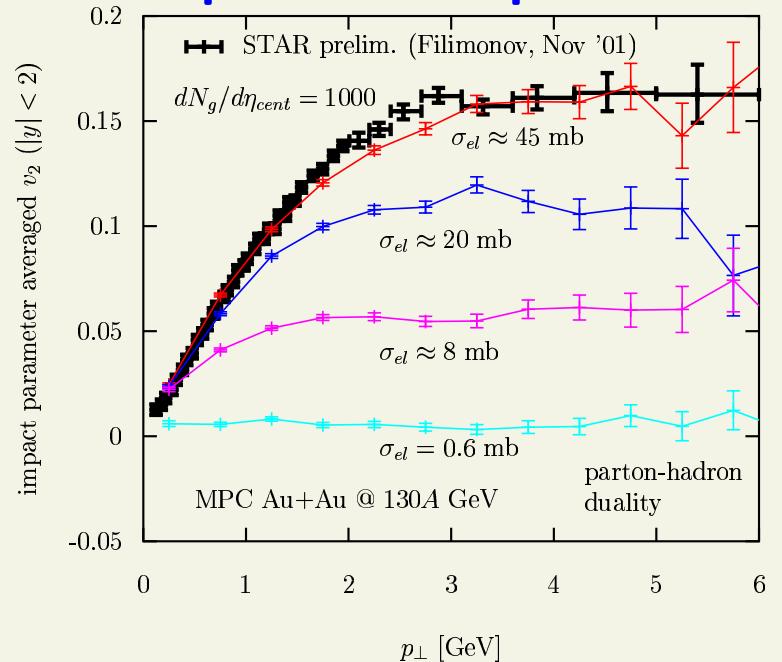
ideal hydrodynamics



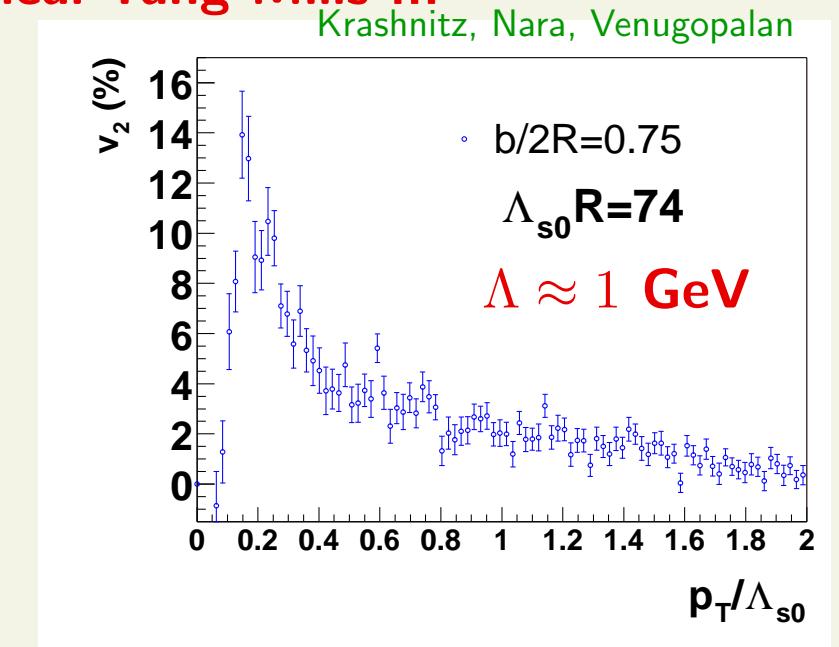
parton energy loss...



covariant parton transport

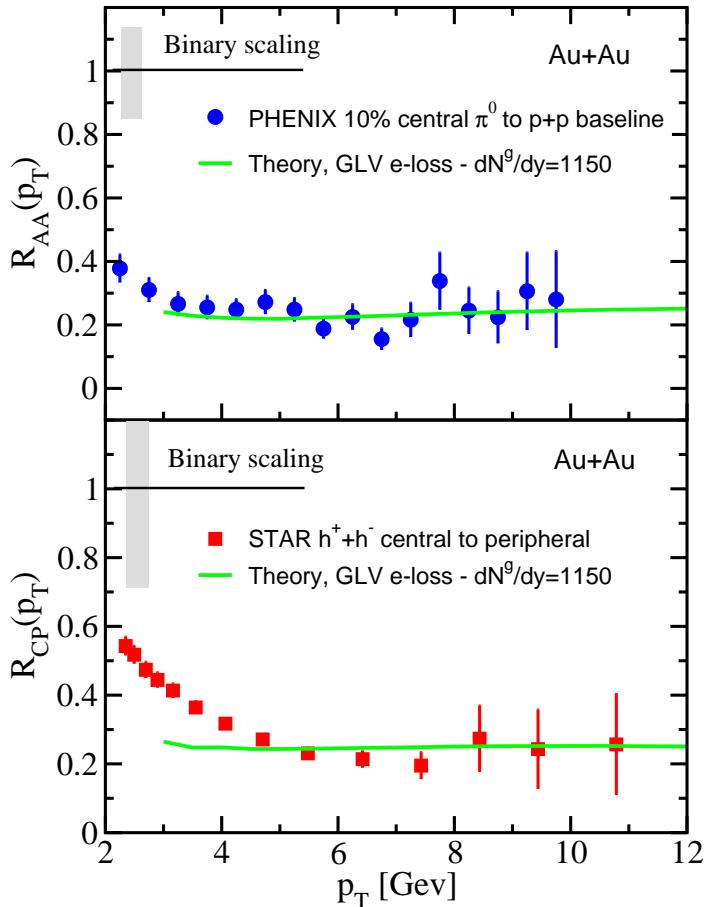


classical Yang-Mills ...

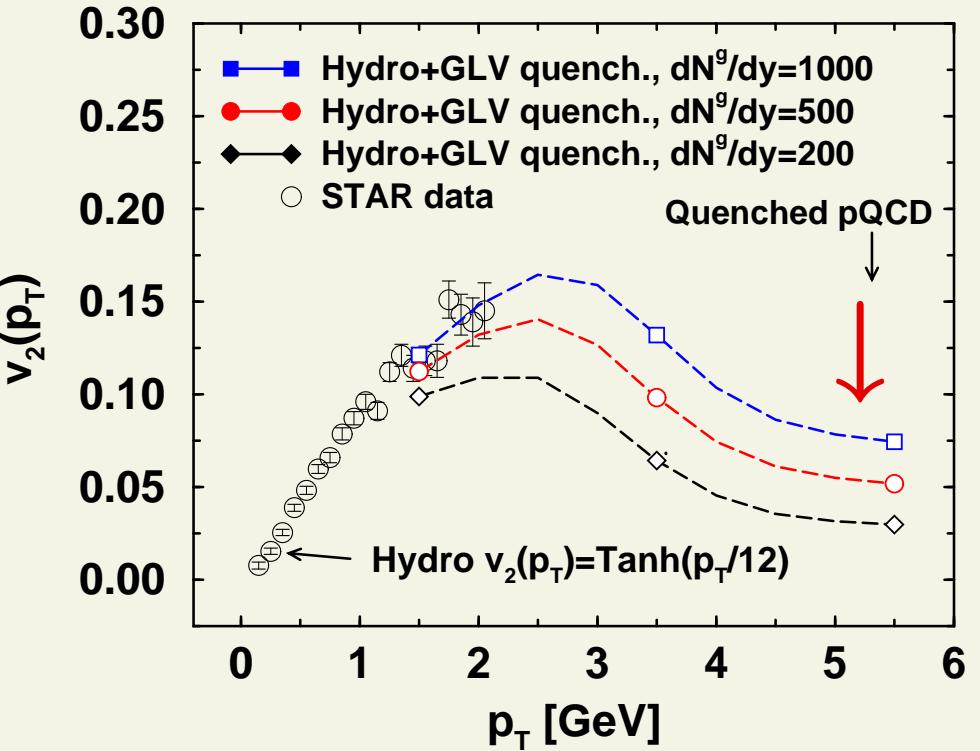


Inelastic parton E-loss with LPM

Vitev, QM2004:



Gyulassy, Vitev, PRL86 '01:



modest ("normal") opacities at RHIC, $N_{coll}(b = 0) \sim 5$, $\lambda_{MFP} \sim 1$ fm

- $dN^{glue}/d\eta \sim 1100$, perturbative cross sections

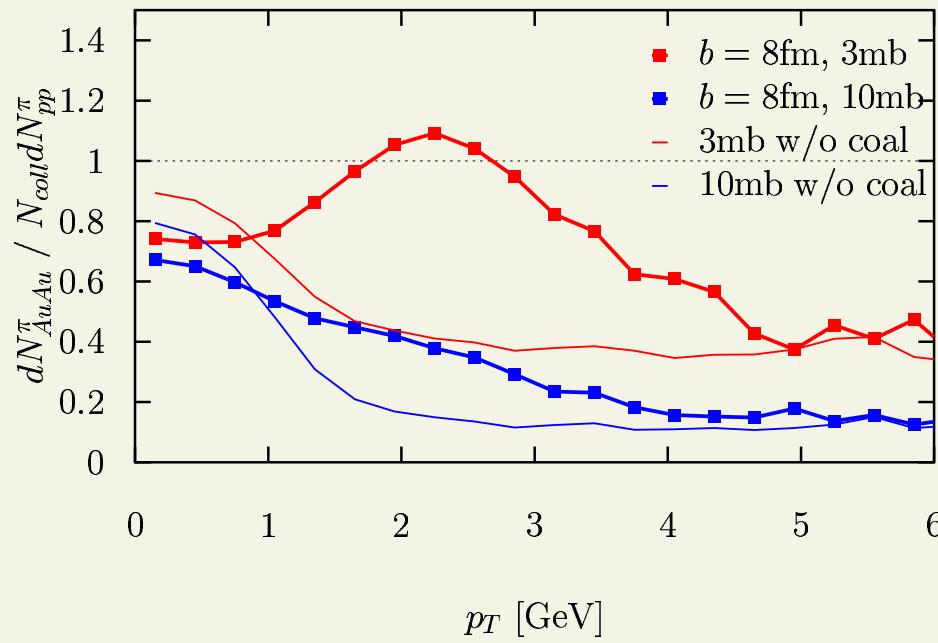
normal for saturation [Eskola, Kajantie et al; McLerran, Kharzeev et al] - HIJING $dN/d\eta \sim 200$

From $2 \rightarrow 2$ kinetic theory

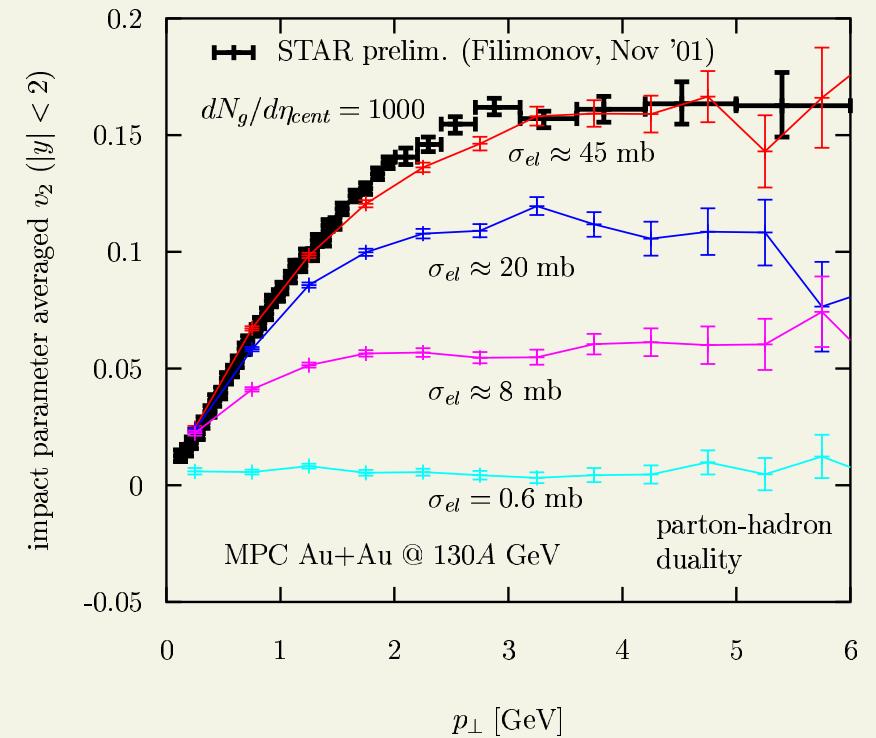
Boltzmann transport - incoherent multiple scatterings $p \cdot \partial f(x, \vec{p}) = C[f]$

Pang, Zhang, Gyulassy, DM, Vance, Csizmadia, Pratt, Cheng, ...

DM, JPG ('04): pion R_{AA}



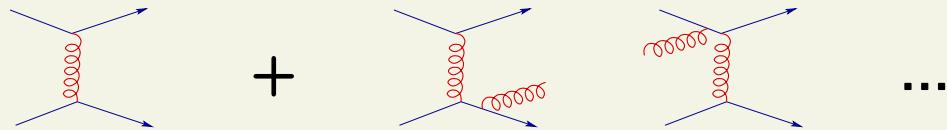
DM, Gyulassy, NPA697 ('02): v_2 from MPC



super-opaque plasma - $N_{coll}(b = 0) \sim 70$, $\lambda_{MFP} \sim 0.1$ fm

- $dN^{glue}/d\eta \sim 1000$, but $15\times$ perturbative cross sections

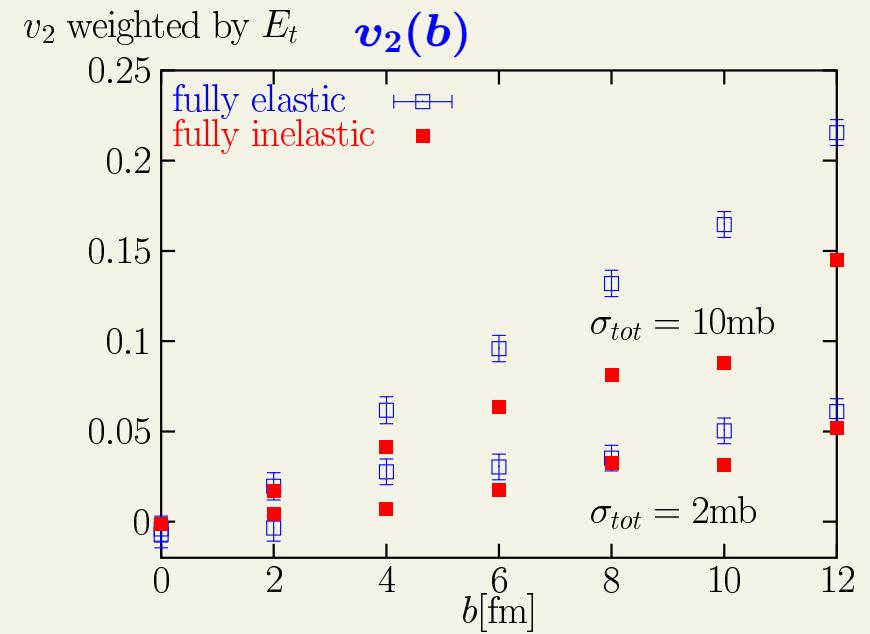
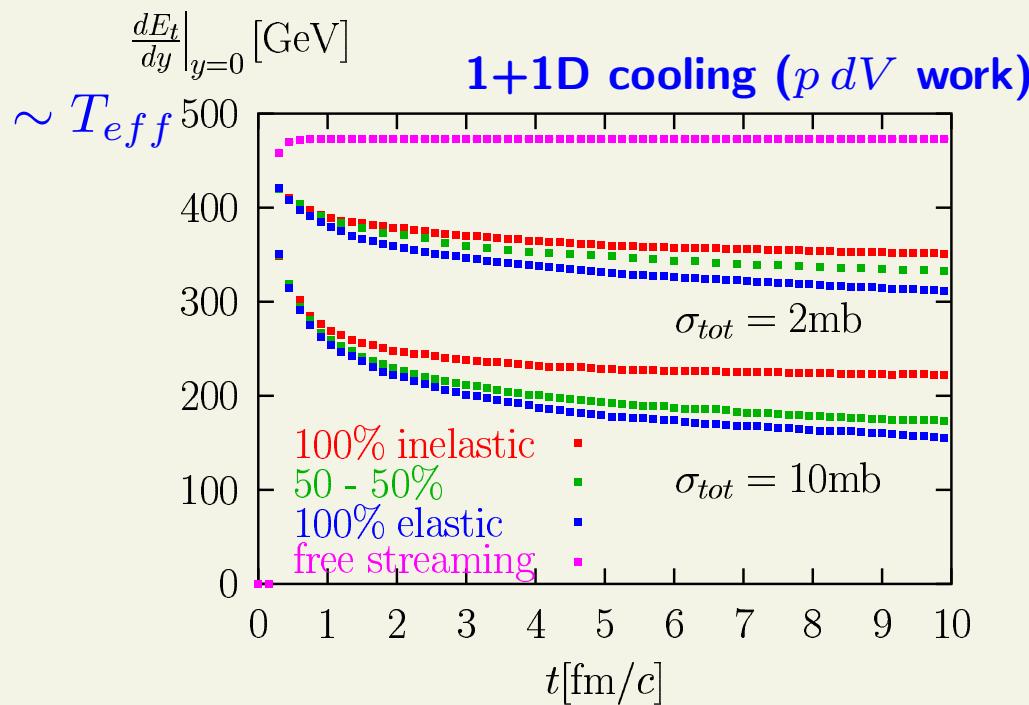
Incoh. radiative transport, $3 \leftrightarrow 2$



$2 \leftrightarrow 3$ proc's enhance effective opacity only 2–3 times → still super-opaque

DM & Gyulassy, NPA 661, 236 ('99): fix transport cross section but vary inelasticity

100% elastic ($2 \rightarrow 2$), 100% inelastic ($3 \leftrightarrow 2$), 50-50% (mixed)

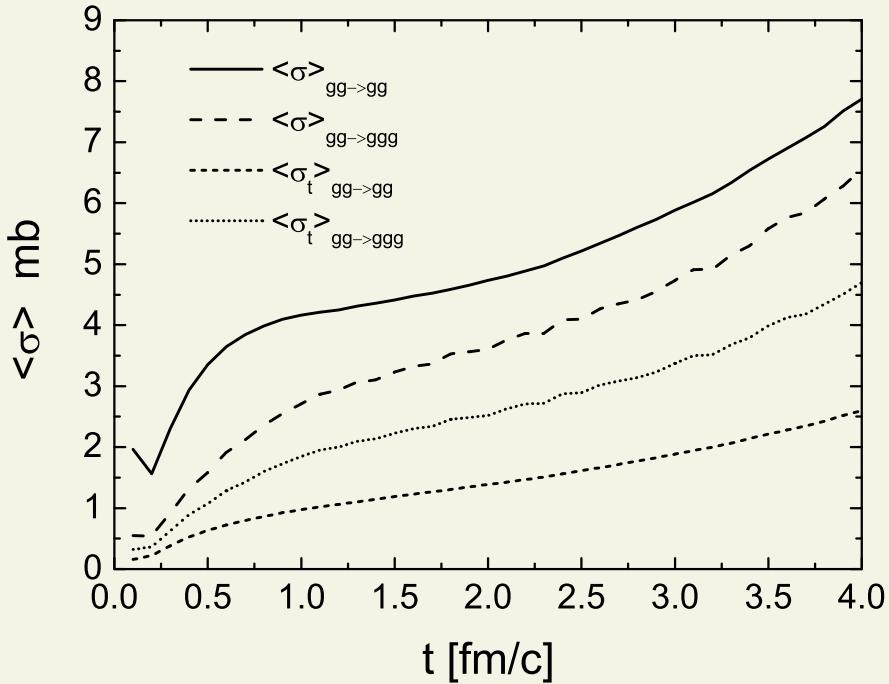


⇒ inelastic $3 \leftrightarrow 2$ is roughly same as elastic with same transport cross section

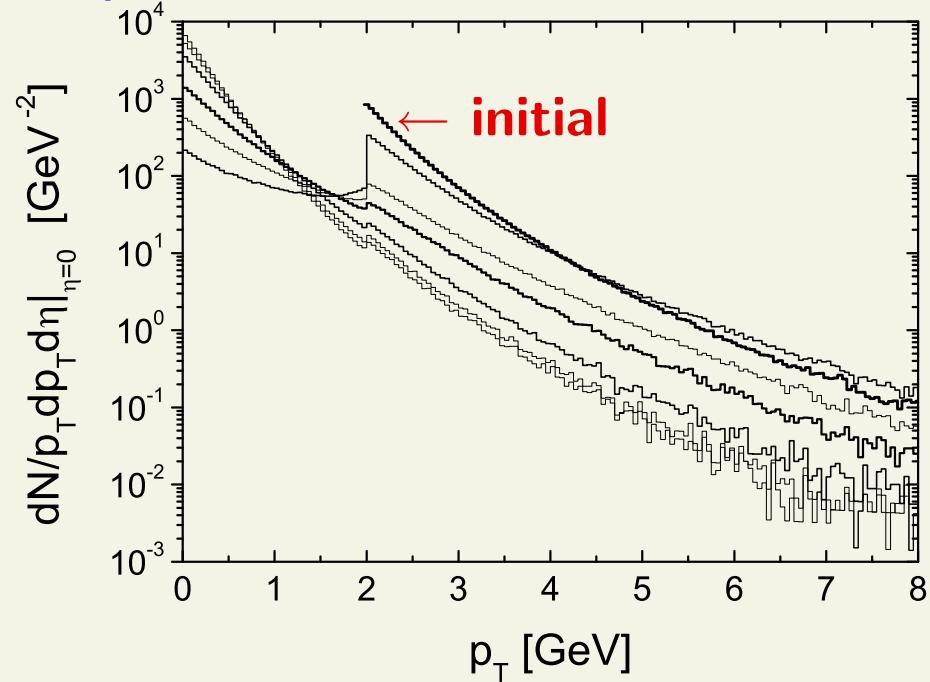
...effect of incoherent $2 \leftrightarrow 3$ still debated - numerics and initial conditions...

Greiner & Xu '04: claim thermalization time-scale $\tau \sim 2 - 3 \text{ fm}/c$

$2 \rightarrow 2, 2 \rightarrow 3$ transport cross sections



spectra vs. time



inel. roughly triples $\sigma_{tr} \leftarrow$ agree

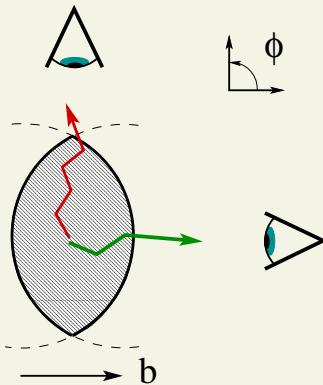
rapid cooling via $2 \rightarrow 3$, because assumed there is nobody below 2 GeV(!)

\Rightarrow driven mostly by phasespace, not collective “pressure” \Rightarrow expect small v_2

in contrast DM & Gyulassy: low- p_T region initially filled $\Rightarrow 3 \rightarrow 2$ active

Coherence very relevant

how to get large v_2 with modest quenching



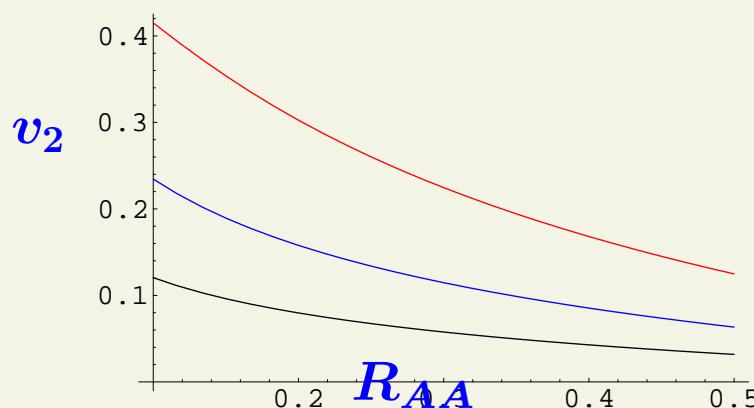
$$\frac{1 - 2v_2}{1 + 2v_2} \approx \frac{R_{AA}(\phi = 90^\circ)}{R_{AA}(\phi = 0)} \Rightarrow \text{need strong length dependence}$$

incoh. multiple scatterings: $\Delta E \propto L$ (static), expect $\Delta E \propto \log(L)$ (Bjorken)

non-Abelian gluon radiation: $\Delta E \propto L^2$ (static), $\Delta E \propto L$ (Bjorken)

DM '05

1



v_2 vs R_{AA} :

$\Delta E \propto L^2$ (static), $\propto L$ (Bjorken)

$\Delta E \propto L^{3/2}$ (static), $\propto L^{1/2}$ (Bjorken)

$\Delta E \propto L^{5/4}$ (static), $\propto L^{1/4}$ (Bjorken)

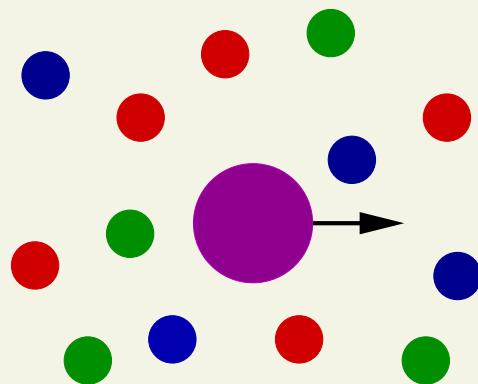
⇒ would be worthwhile to combine GLV with the (incoherent) transport

Cross-check/new angle: heavy quarks

- **mass matters** - weaker randomization, less energy loss
- **good test** - fix params to light sector, then look at heavy flavor

“Brownian motion” in plasma

$$m_g, m_{u,d}, m_s \sim T$$



$$m_c \sim 1.2 \text{ GeV} \gg T$$

$$v \sim \sqrt{T/m}$$

$$p \sim \sqrt{m \cdot T}$$

$$N_{coll} \sim p/\Delta q \sim \sqrt{m/T}$$

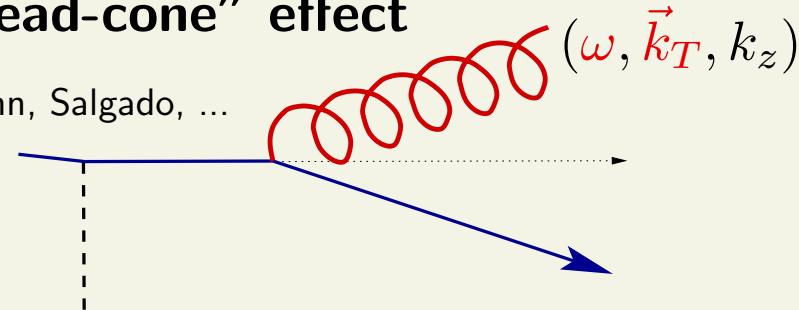
heavy quarks \Rightarrow need more collisions to randomize

suppressed radiation/smaller energy loss - “dead-cone” effect

Dokshitzer, Kharzeev, Gyulassy, Djordjevic, Wiedemann, Salgado, ...

massive q :

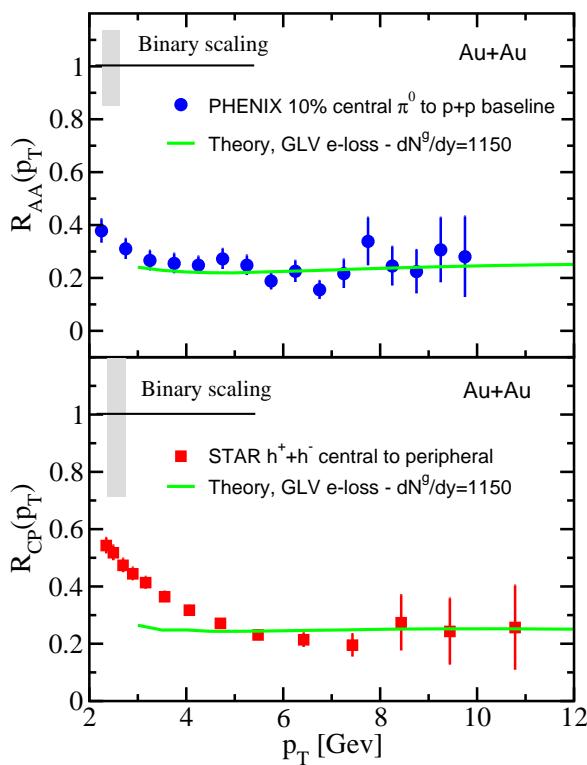
$$\frac{dN_g}{d\omega dk_T^2} = \frac{4\alpha_s}{3\pi} \frac{k_T^2}{\omega(k_T^2 + \omega^2 M^2/E^2)^2}$$



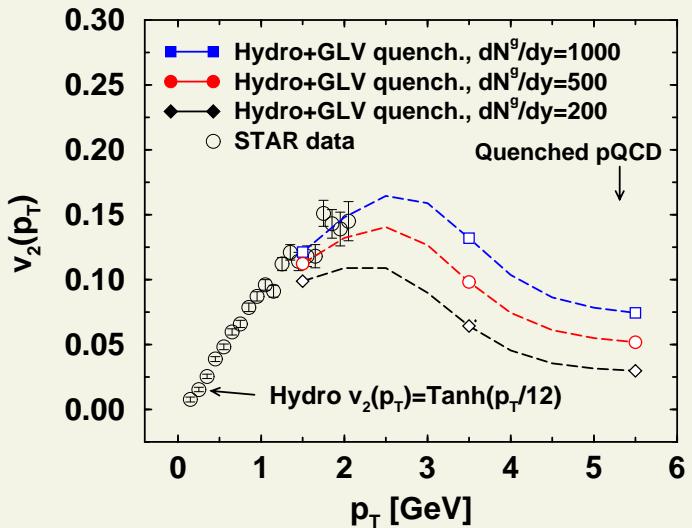
most reduction at small angles $\theta \approx k_T/\omega < \sim M/E$

similar expectations for medium-induced radiation

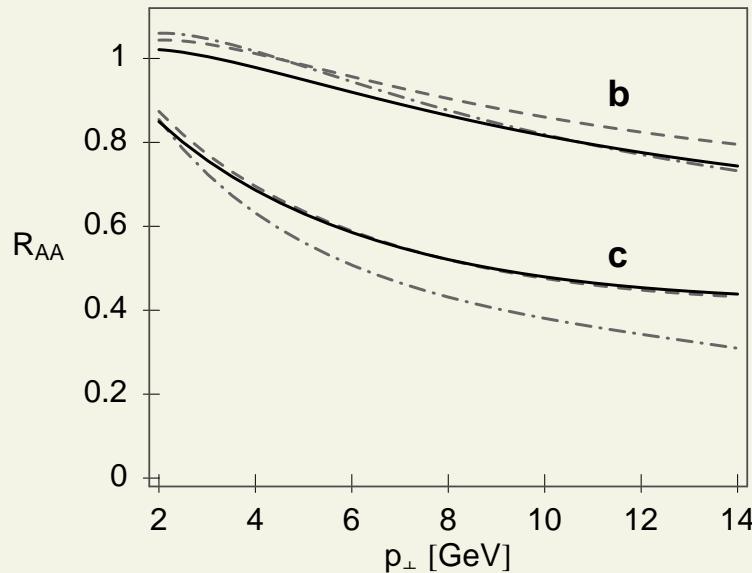
Vitev @ QM2004: **light g,q**



Gyulassy, Vitev '01: **light** $v_2 \sim 7\%$



Djordjevic, Gyulassy, Wick '04: **heavy c,b**



\Rightarrow **DGLV: much weaker high-pT suppr.**

DM @ SQM2004, estimate:

heavy-q $v_2 \sim 20\%$ below **light hadron** v_2

$$\frac{1 - 2v_2}{1 + 2v_2} \approx \frac{R_{AA}(\phi = 90^\circ)}{R_{AA}(\phi = 0)} \Rightarrow v_2^{\text{charm}} \sim 5 - 6\%$$

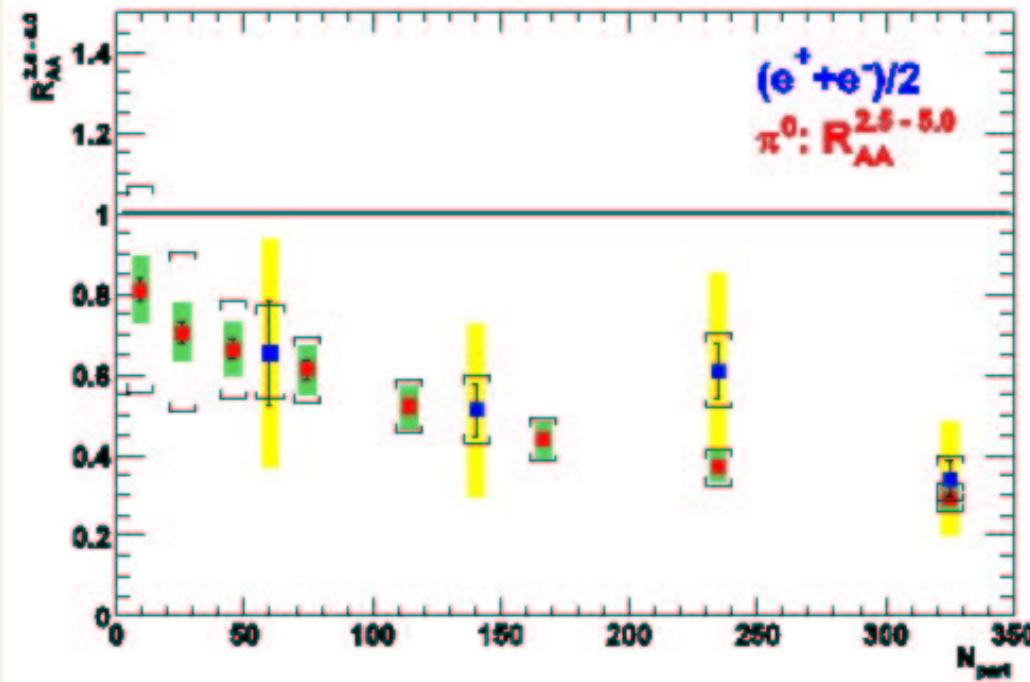
($\Delta E/E(0) \approx 0.36$, $\Delta E/E(90^\circ) \approx 0.42$

fluctuations in $\Delta E \rightarrow$ use $0.5\langle\Delta E\rangle \equiv \delta$

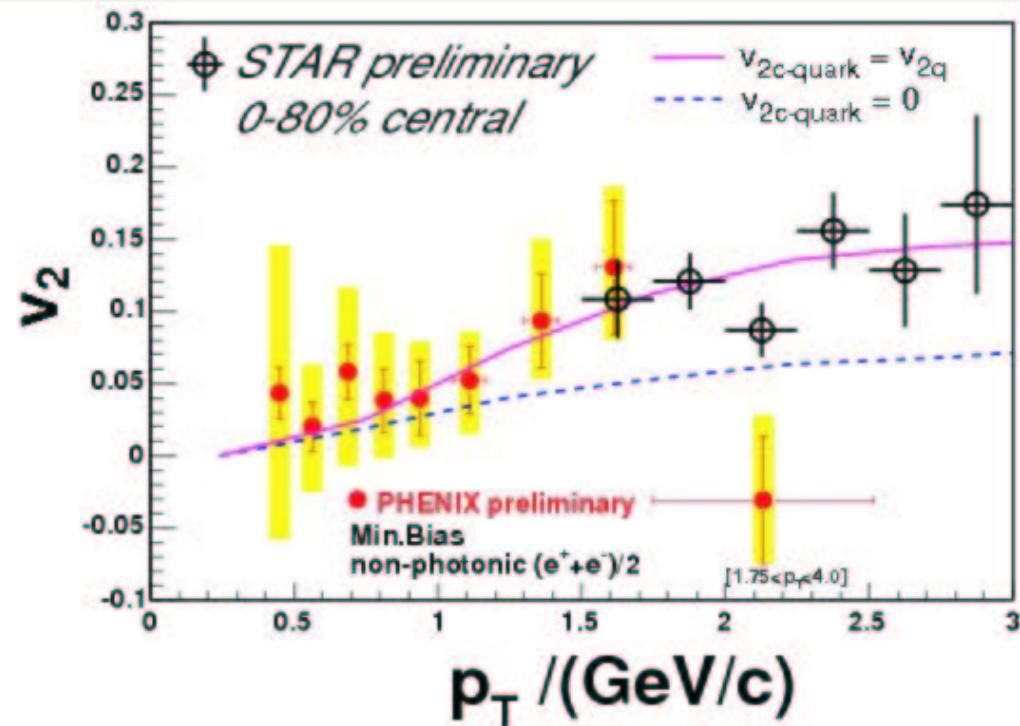
power law $\frac{dN}{dp_T} \sim p_T^{-\alpha} \Rightarrow R_{AA} \approx (1 - \delta)^{\alpha-1}$, take $\alpha = 7$)

Heavy flavor - prelim. RHIC data

PHENIX '05: same light & heavy R_{AA} (!)



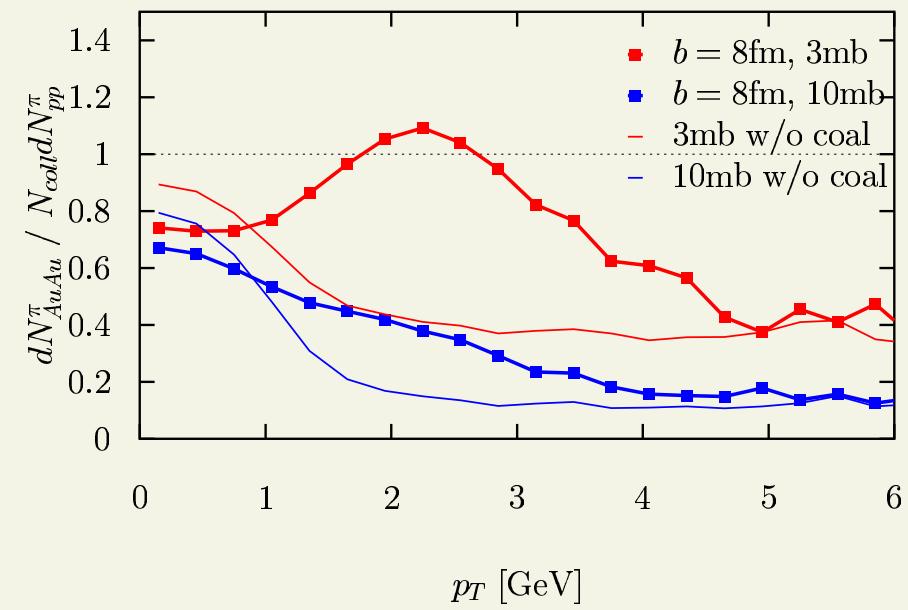
STAR,PHENIX '04: similar high-pT v_2 (!)



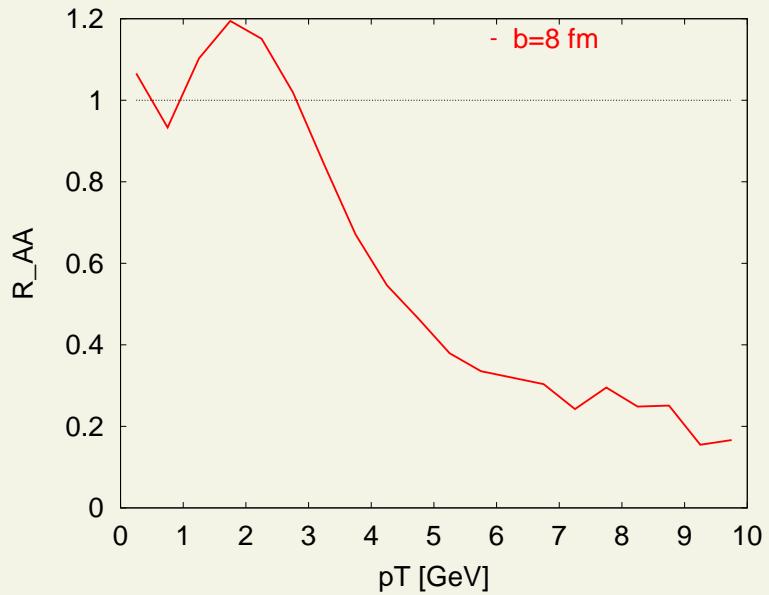
see little difference between light and heavy flavor (for $p_T > 2 - 2.5$ GeV)

does this support the super-opaque plasma then?

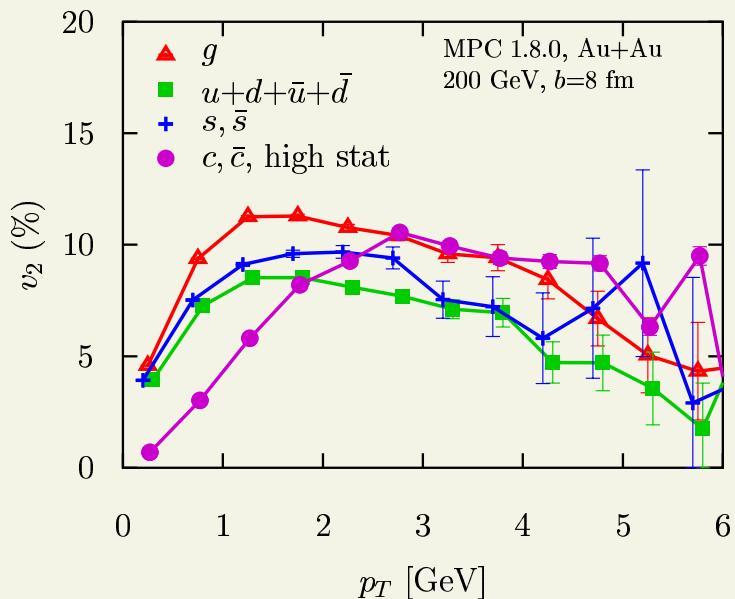
DM '04: **light** R_{AA}



DM '04: **charm** R_{AA}



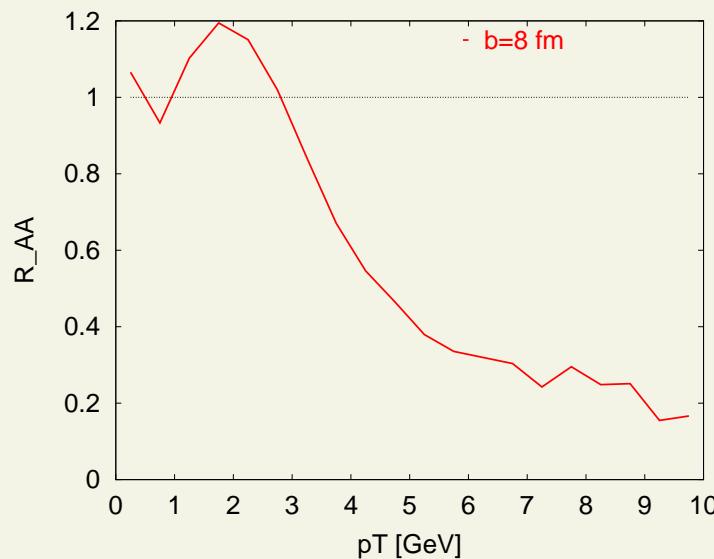
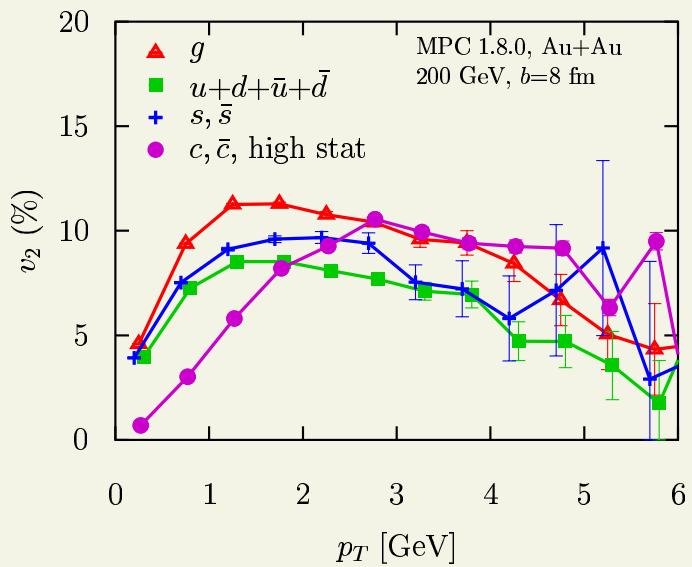
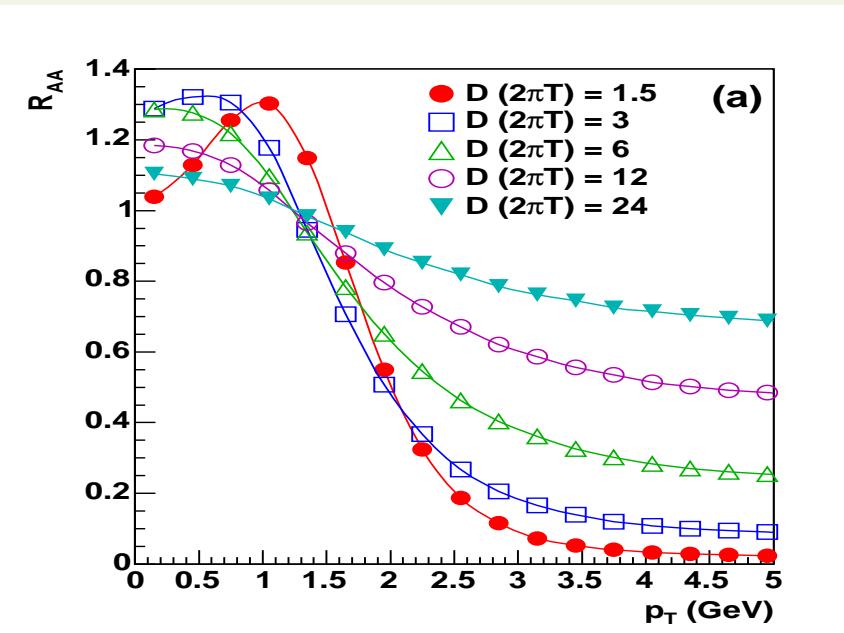
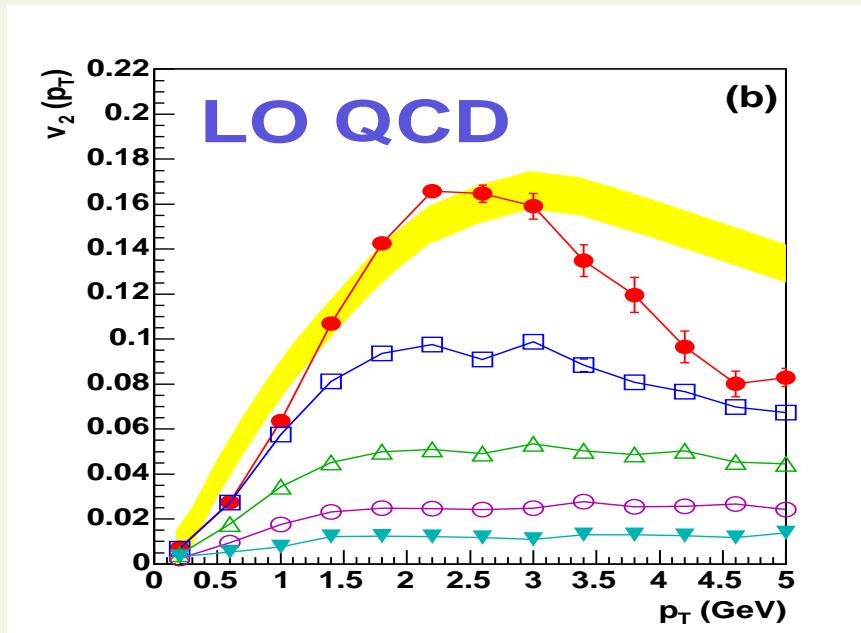
charm v_2 - prediction



qualitatively better

- **charm v_2 same as light v_2 at high p_T**
- **but R_{AA} is higher (closer to data)**

qualitatively similar to Langevin approx. (random Gaussian force) Teaney,
 Arnold '04 - but quantitative differences



assume: all $2 \rightarrow 2$ processes are enhanced by **same factor** in opaque plasma

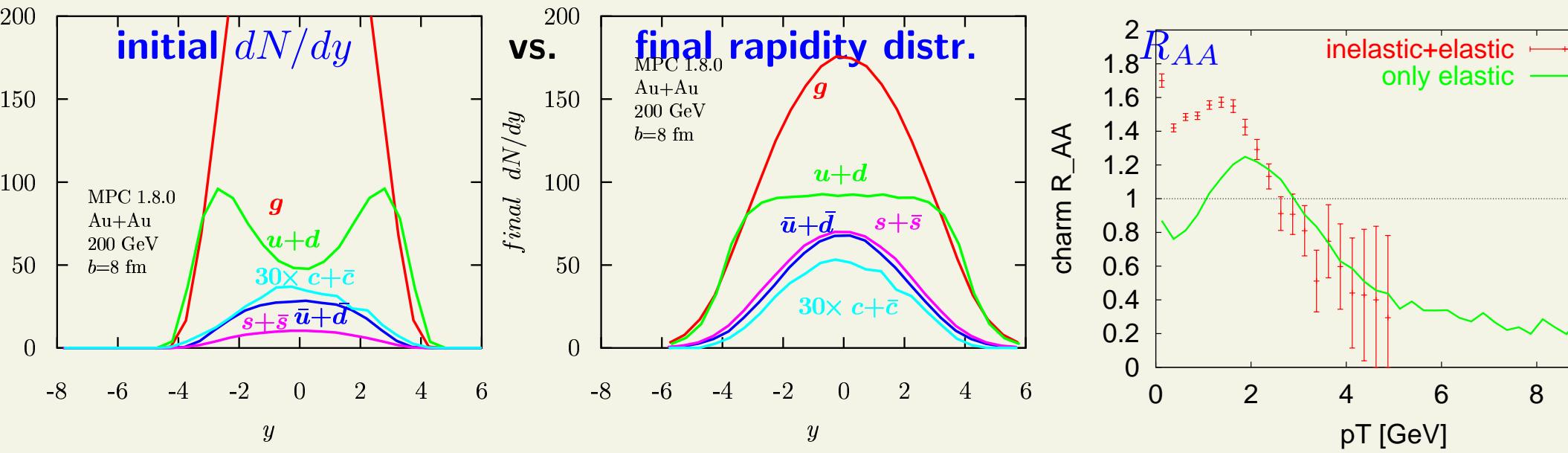
based on Combridge NPB 151 ('79) 429:

$$\begin{aligned}\sigma_{gg \rightarrow q\bar{q}} &= \frac{2r}{27} \frac{1+r}{1+2r} \ln\left(1 + \frac{1}{r}\right) \sigma_{gg \rightarrow gg}, \quad \sigma_{q_i\bar{q}_i \rightarrow q_j\bar{q}_j} = \frac{16r}{243} \sigma_{gg \rightarrow gg} \\ \sigma_{gg \rightarrow c\bar{c}} &= \frac{2r}{27} \Theta(1-4R) \left[(1+4R+R^2) \ln \frac{1+\sqrt{1-4R}}{1-\sqrt{1-4R}} - (7+3R) \frac{\sqrt{1-4R}}{4} \right] \sigma_{gg \rightarrow gg} \\ \sigma_{q\bar{q} \rightarrow c\bar{c}} &= \frac{16r}{243} \Theta(1-4R)(1+2R)\sqrt{1-4R} \sigma_{gg \rightarrow gg}\end{aligned}$$

where $r \equiv \mu_D^2/s$, $R \equiv M_c^2/s$

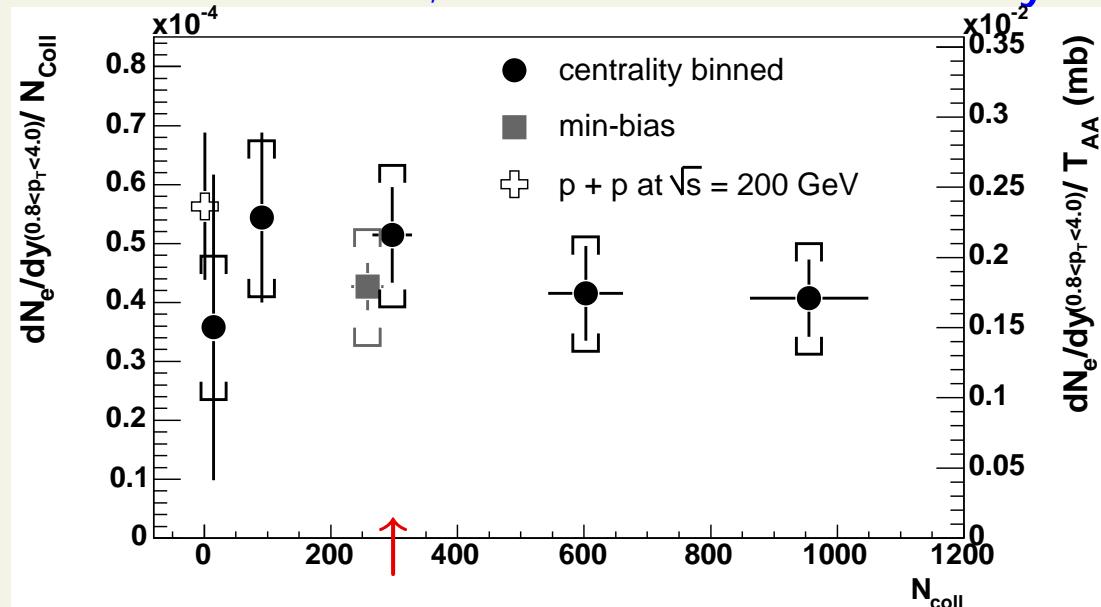
take $\mu_D = 0.7 \text{ GeV}$, $M_c = 1.2 \text{ GeV}$

DM, JPG ('04): significant secondary charm production



half the glue fuse to $q\bar{q}$, strangeness up $5\times$, also extra $40 - 50\%$ charm yield

BUT: data PHENIX, PRL94 '05 - no secondary charm (collision scaling)



Origin of high-pT particles

- jet energy loss + fragmentation?
- coalescence vs fragmentation?
- soft tails?

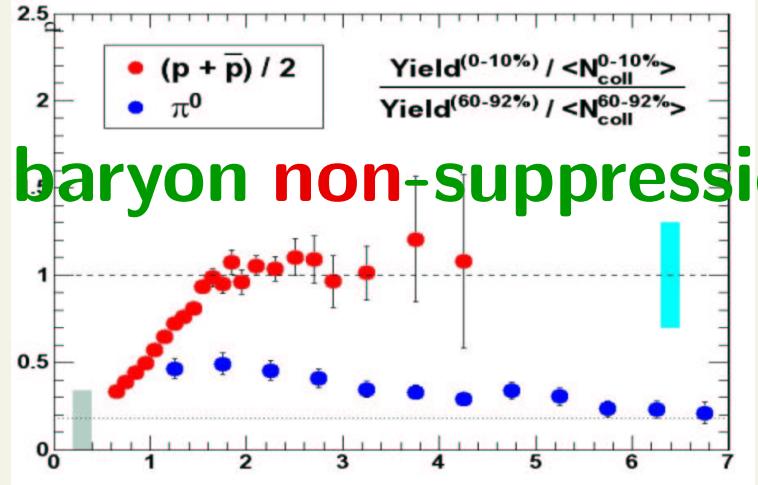
how high pT is “high enough”?

- hadronization uncertainties

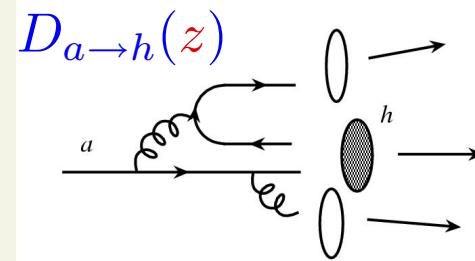
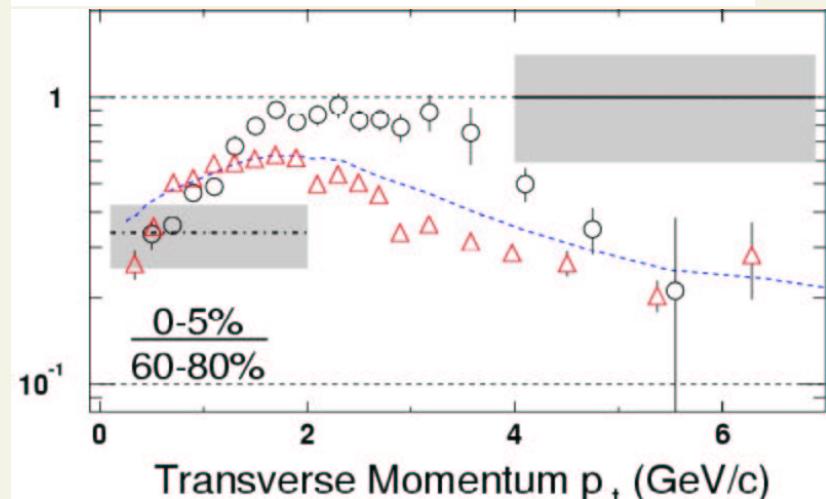
Baryon/meson puzzle

factorization $dN_h = f_i \otimes f_j \otimes d\sigma_{ij \rightarrow a} \otimes \Delta E \otimes D_{a \rightarrow h}$ fails for baryons in A+A

d'Enterria [PHENIX], Sorensen [STAR]:

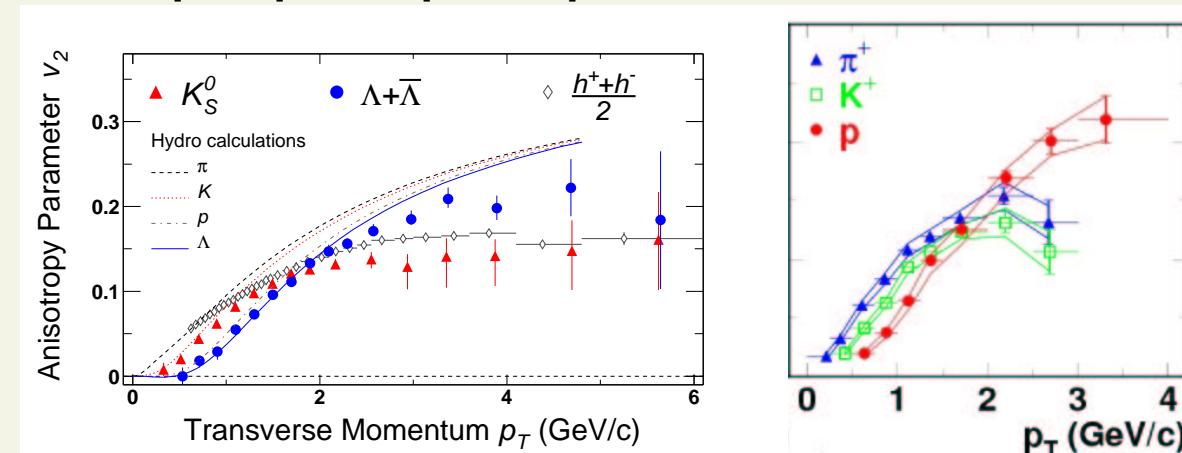


baryon non-suppression



baryon/meson elliptic flow split at high p_T

Sorensen [STAR], Esumi [PHENIX]:



Is it mass, or quark content?

decisive test: **proton vs phi meson** - until then, ideas:

mass:

- power corrections $\mathcal{O}(m^2/Q^2)$
- hydrodynamic effects $p \cdot u$

valence quarks: - coalescence hadronization

Quark coalescence

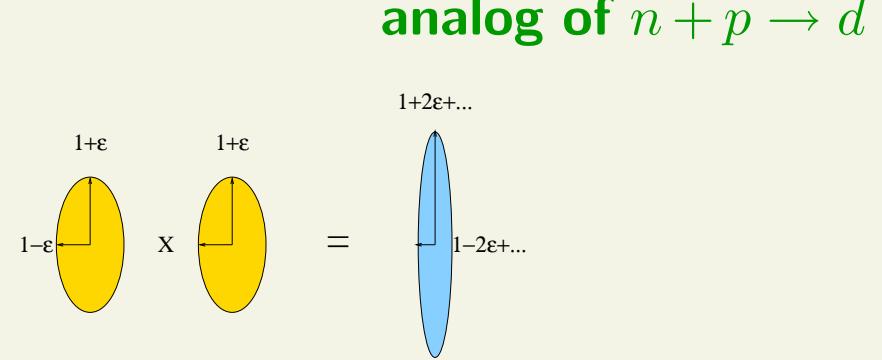
Ko, Lin, Voloshin, DM, Greco, Levai, Mueller, Fries, Bass, Nonaka, Asakawa ...

coalescence of comoving quarks: $q\bar{q} \rightleftharpoons M$ $3q \rightleftharpoons B$

DM & Voloshin, PRL91 ('03)

$$\frac{dN_M(p_T)}{d\phi} \propto \left[\frac{dN_q(p_T/2)}{d\phi} \right]^2$$

$$\frac{dN_B(p_T)}{d\phi} \propto \left[\frac{dN_q(p_T/3)}{d\phi} \right]^3$$

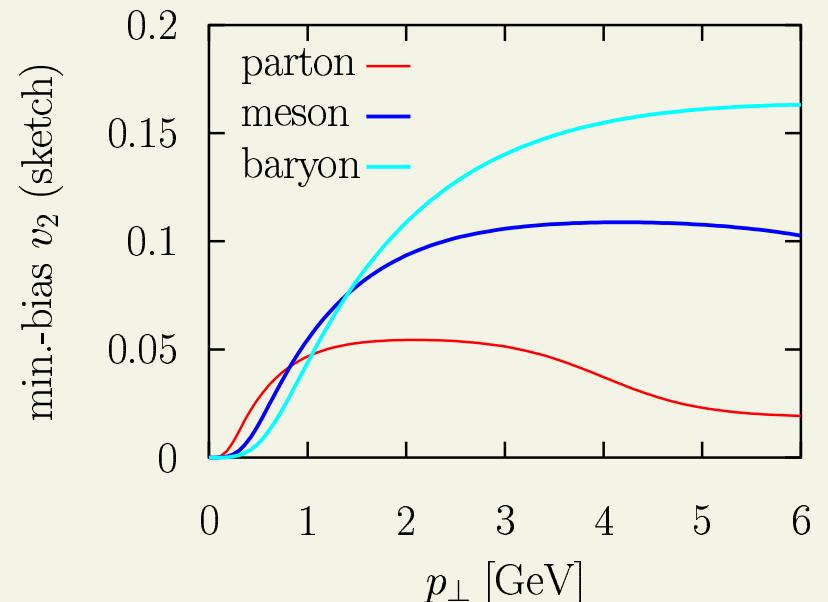


squared/cubed probability → **amplified v_2**

$$v_2^{\text{hadron}}(p_\perp) \approx n \times v_2^{\text{quark}}(p_\perp/n)$$

3× for baryons } **50% larger v_2**
2× for mesons } **for baryons**

→ 5× for pentaquark, 6× for deuteron



amplification greatly reduces opacities needed to reproduce v_2 data

coalescence gives a reversal in trends

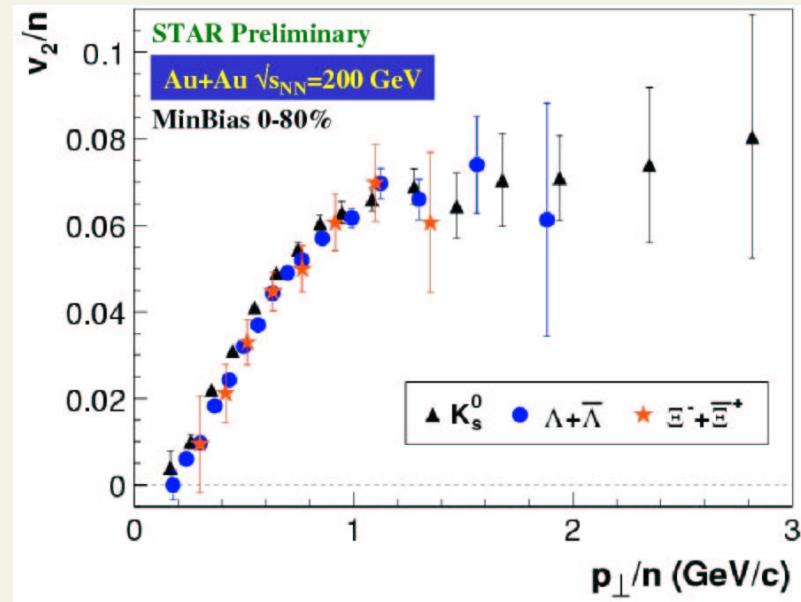
effect of opacity increase: v_2 up, R_{AA} down

effect of coalescence: v_2 up, R_{AA} up at hadronization

picture hangs together nicely, if quark final state distr. is a fit parameter

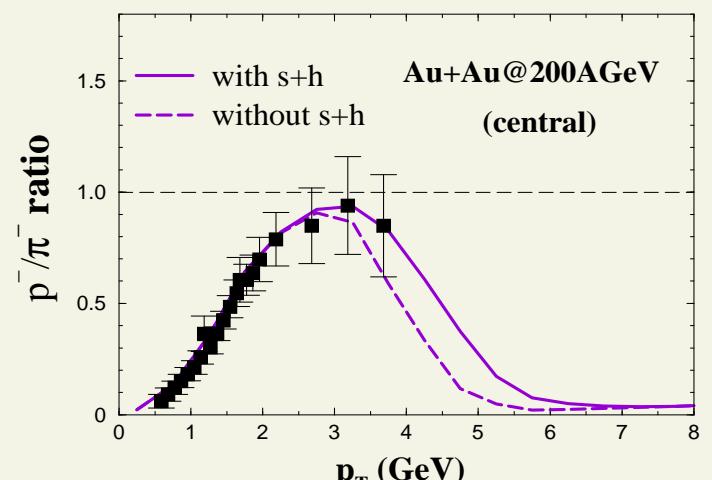
quark number scaling at RHIC

Castillo [STAR], HIC03: K_S^0, Λ, Ξ



pion/proton ratio - coal window $pT < 5-6$ GeV

Greco, Ko, Levai, PRL90 ('03):



only partons near in phasespace can fuse - “coalescence formula”:

$$\frac{dN_M(\vec{p})}{d^3p} = g_M \int \left(\prod_{i=1,2} d^3x_i d^3p_i \right) W_M(x_1-x_2, \vec{p}_1 - \vec{p}_2) f_\alpha(\vec{p}_1, x_1) f_\beta(\vec{p}_2, x_2) \delta^3(\vec{p} - \vec{p}_1 - \vec{p}_2)$$

$$\frac{dN_B(\vec{p})}{d^3p} = g_B \int \left(\prod_{i=1,2,3} d^3x_i d^3p_i \right) W_B(x_{12}, x_{13}, \vec{p}_{12}, \vec{p}_{13}) f_\alpha(\vec{p}_1, x_1) f_\beta(\vec{p}_2, x_2) f_\gamma(\vec{p}_3, x_3) \delta^3(\vec{p} - \sum \vec{p}_i)$$

hadron yield space-time hadron wave-fn. quark distributions

gives v_2 scaling trivially if:

1. no other hadronization channels play a role
2. narrow hadron wave functions $W \sim \delta^3(\Delta x) \delta^3(\Delta p)$ - or small phasespace variations
3. only small local harmonic modulations $|v_2(\mathbf{x})| \ll 1, |v_n(\mathbf{x})| \ll 1$

$$v_2^{Meson}(p_T) = \frac{2 \langle f_q^2(\mathbf{x}, p_T/2) v_{2,q}(\mathbf{x}, p_T) \rangle_{\mathbf{x}}}{\langle f_q^2(\mathbf{x}, p_T/2) \rangle_{\mathbf{x}}}$$

$$v_2^{Baryon}(p_T) = \frac{3 \langle f_q^3(\mathbf{x}, p_T/3) v_{2,q}(\mathbf{x}, p_T) \rangle_{\mathbf{x}}}{\langle f_q^3(\mathbf{x}, p_T/3) \rangle_{\mathbf{x}}}$$

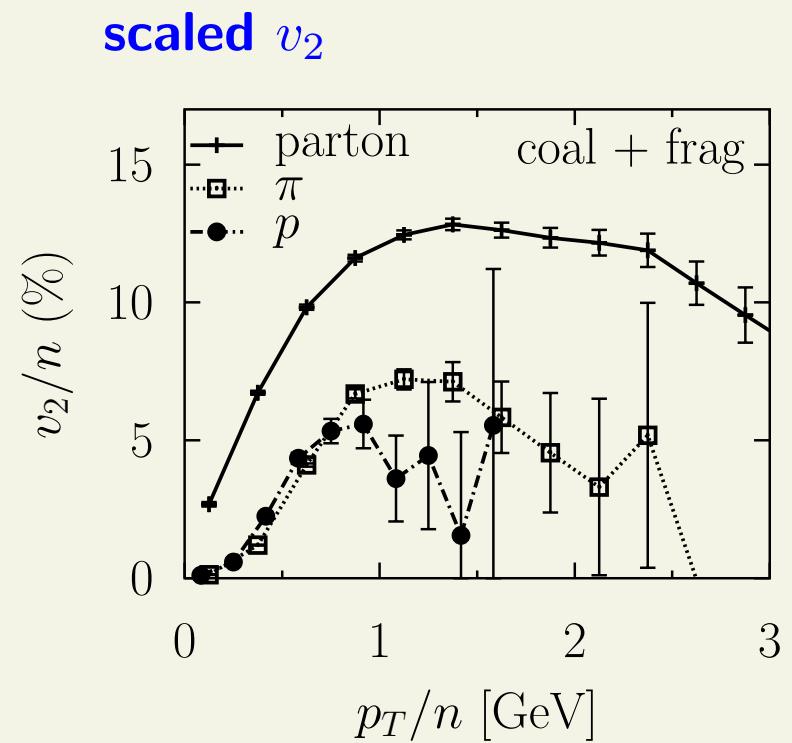
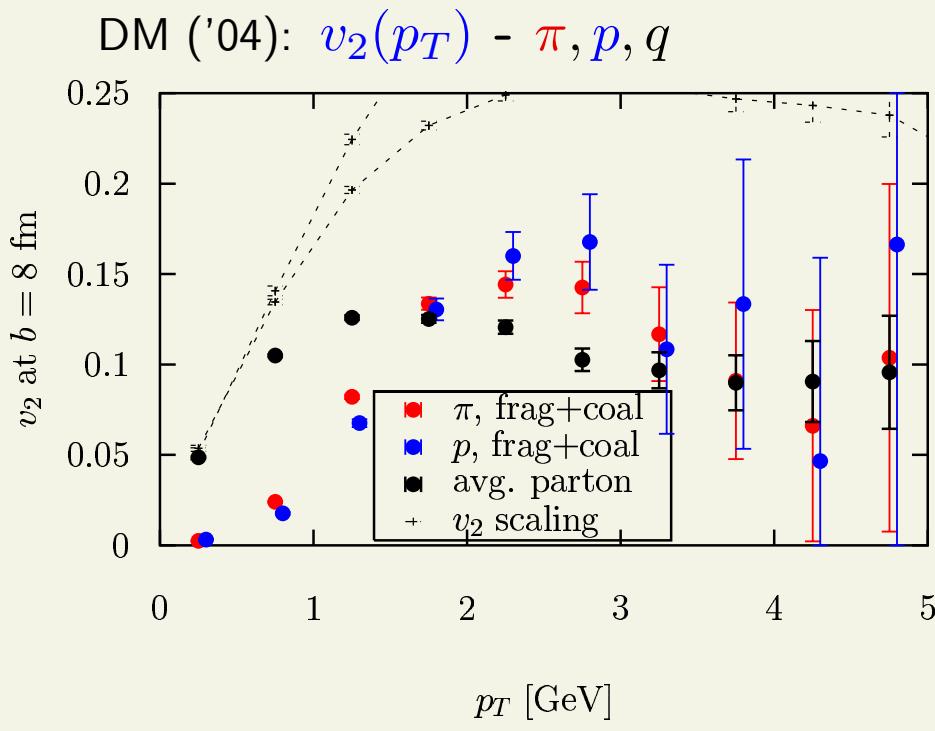
4. spatial dependence can be ignored (factorizes out) $\Rightarrow v_2^{hadron}(p_T) = n v_2^{quark}(p_T/n)$
 - for example, global $v_2(x, p_T) \equiv v_2(p_T)$, or constant FO phasespace density

none of these satisfied in transport or hydro, contrary to parameterizations

Quark number scaling is truly puzzling for dynamics

- significant fragmentation contributions
- strong space-momentum correlations (spatial anisotropies)
- surface emission, strongly peaked angular distributions

parton transport + dynamical 4D coalescence - Gyulassy, Frankel, Remler '83
and indep fragmentation - JETSET for partons without coal partner



flow amplification greatly reduced, baryon-meson splitting mostly gone

may still scale approximately $\sim 15\%$ err but scaled v_2 is NOT the quark v_2

Soft physics tails at high pT(!)

partons can end up with some final parton momentum (p_T , y) in three ways:

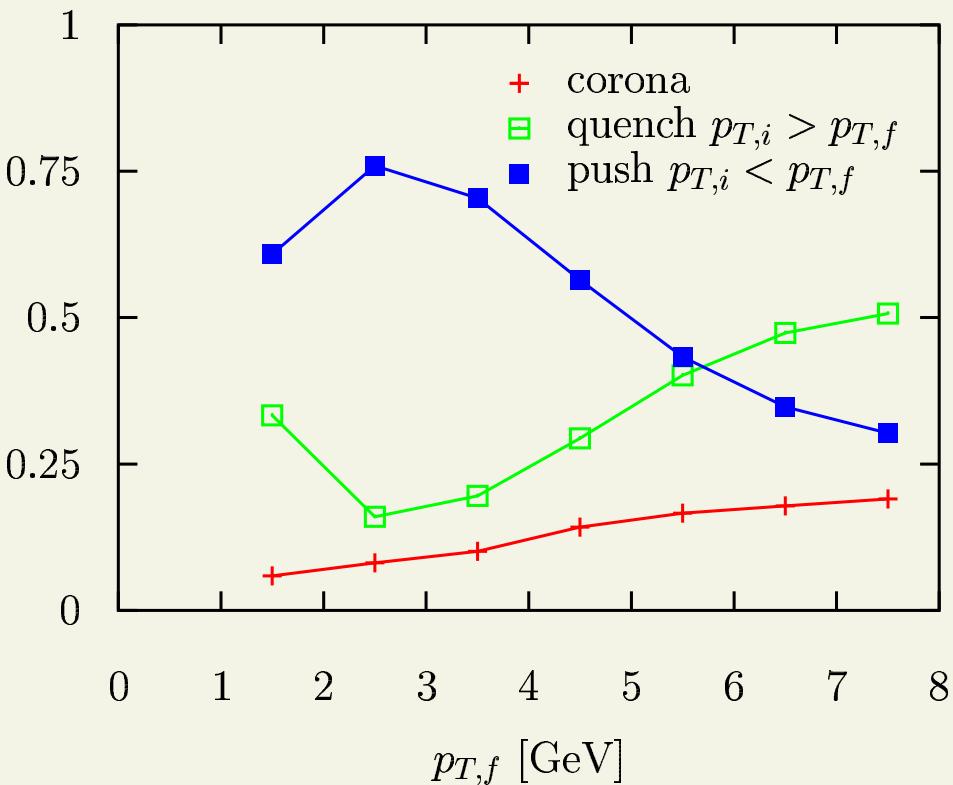
- escape with no interaction - corona
- interact and lose energy - quench
- 3rd possibility: interact and gain energy - “push”

in opaque plasma, gain component can be relevant at surprisingly high p_T , pushing “pure” hard physics out to $p_T \gtrsim 10$ GeV

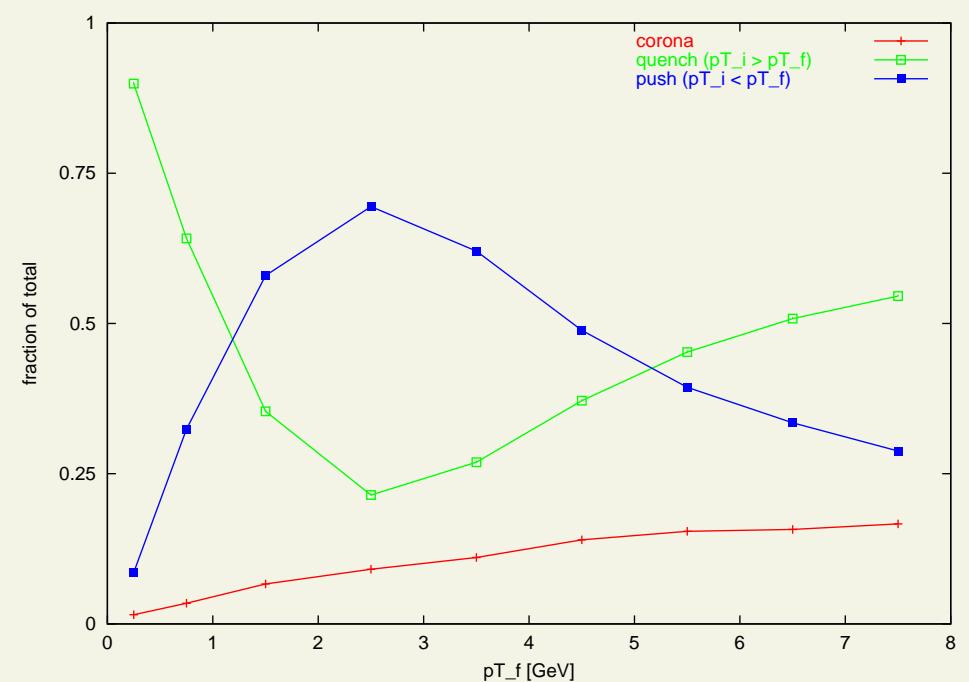
study using MPC 1.8.0 w/ elastic and inelastic $2 \rightarrow 2$, $dN^{cent}/d\eta = 2000$

fractions from corona, quench, push vs pT, ($|y_f| < 1$)

DM, nucl-th/0503051: $\sigma_{gg} = 10 \text{ mb}$



$\sigma_{gg} = 5 \text{ mb}$



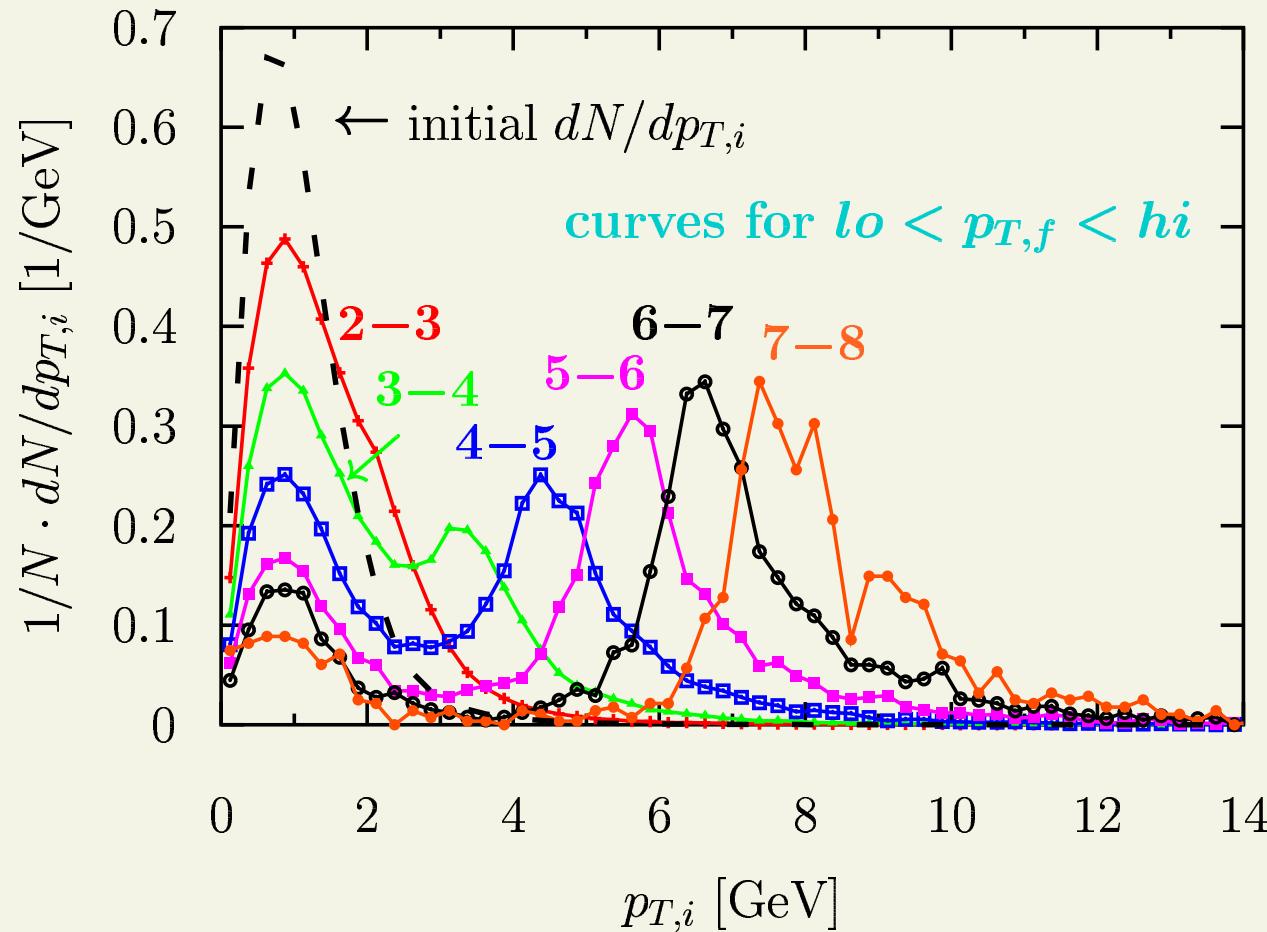
corona and “push” are significant even at $p_{T,parton} \sim 8 \text{ GeV}$

fractions show surprisingly weak opacity dependence

distribution of initial momenta for fixed final momentum bins, $|y_{fin}| < 1$

(only quench + “push” plotted, normalized)

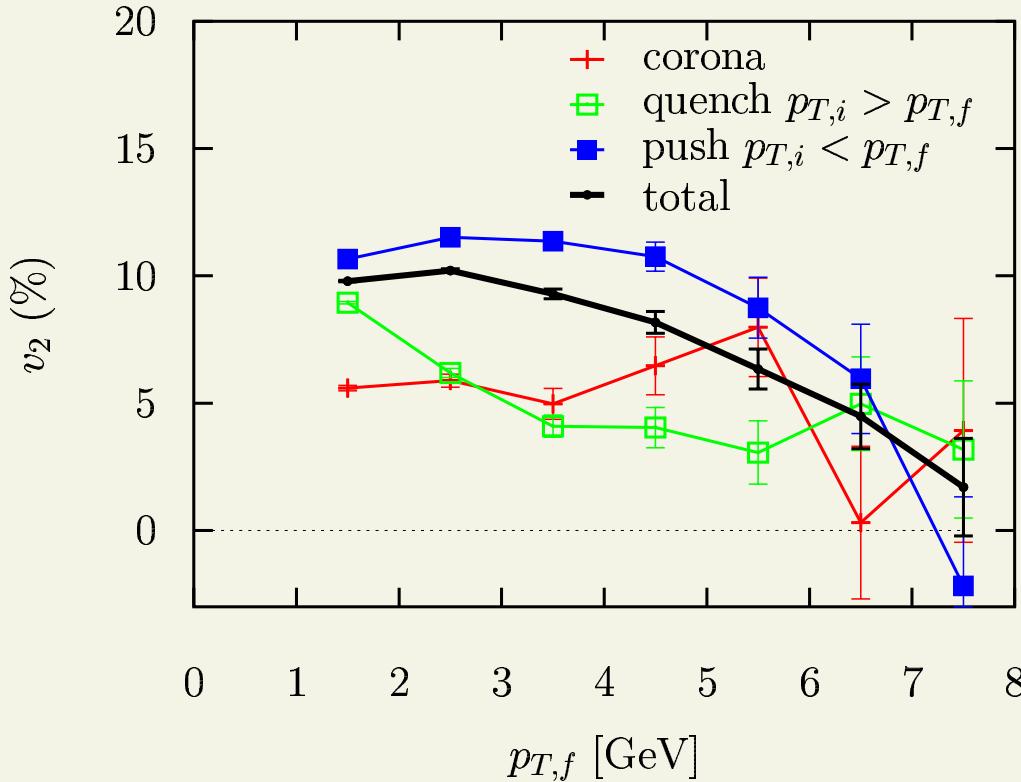
DM, nucl-th/0503051: $\sigma_{gg} = 10 \text{ mb}$



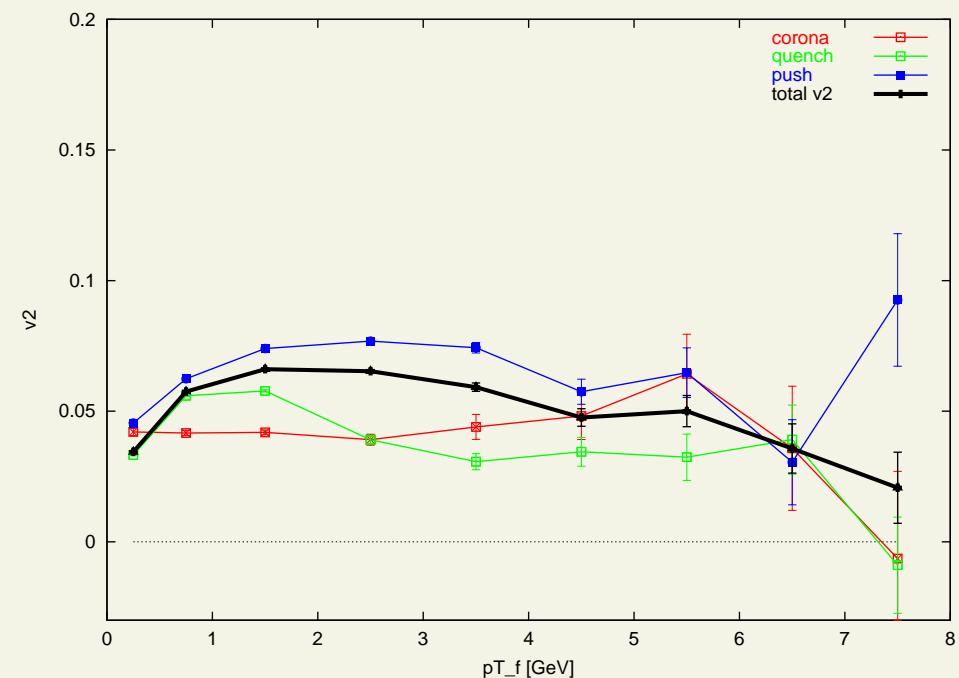
“lucky” $p_{T,i} \sim 1 \text{ GeV}$ soft partons can end up at $p_T \sim 5 - 6 - 7 \text{ GeV}$

elliptic flow contributions vs pT

DM, nucl-th/0503051: $\sigma_{gg} = 10 \text{ mb}$



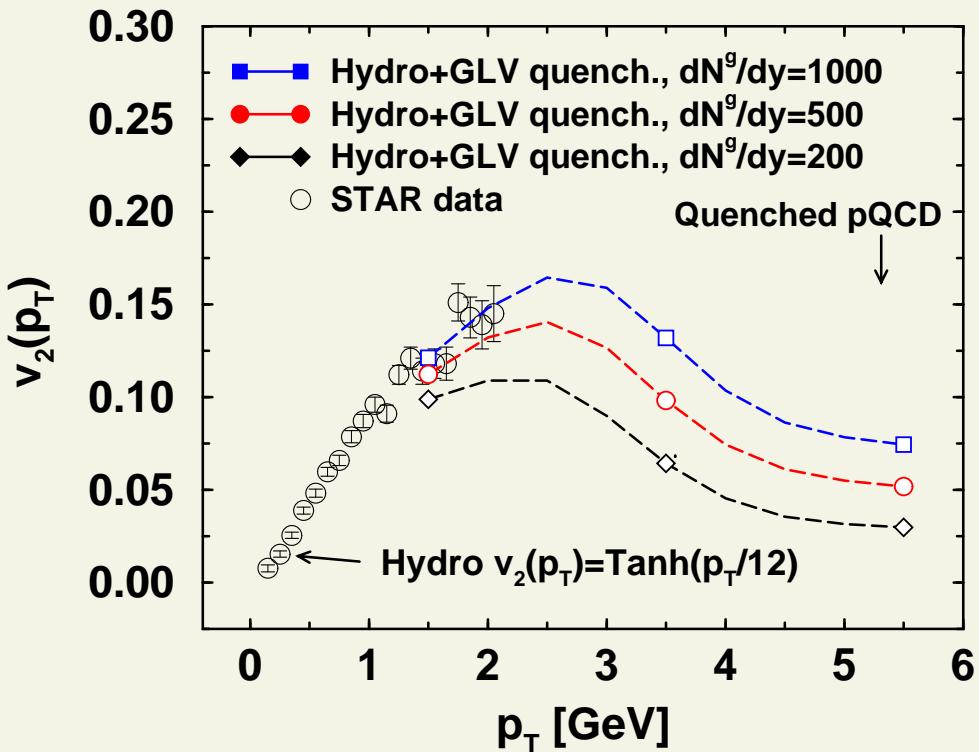
$\sigma_{gg} = 5 \text{ mb}$



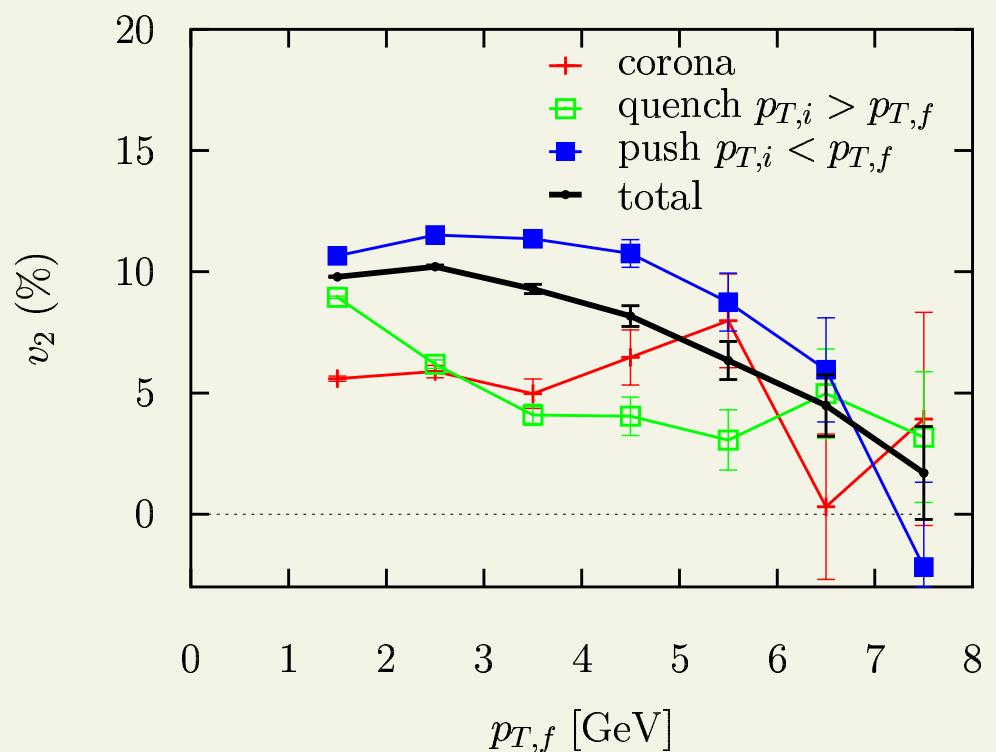
rapid v_2 drop from quench at high p_T is compensated by large v_2 of “pushed-up” partons

combined $v_2(p_T)$ decreases more slowly at high p_T and can exceed “geometric” (extreme absorption) bounds Shuryak ('04), Voloshin ('04)

Gyulassy & Vitev PRL86 '01: **inel. (GLV)**



DM '05: **elastic (MPC)**



quench v_2 is very similar, drops fast at large $p_T \gtrsim 3$ GeV, in both cases(!)

despite the rather different dynamical origin

Summary

- High-pT observables also reflect space-time dynamics in a heavy-ion collision - low and high pT regions are coupled. Dynamical uncertainties give systematic errors for quantities extracted from high-pT observables. E.g.,
 - role of (ignored) quarks in medium
 - dissipation (viscosity)
- Magnitude and origin (mechanism) of parton opacity is still a puzzle - mixed indications for super-opaque plasma and/or modest perturbative opacities.
 - light R_{AA} vs v_2 inconsistency → more suggests GLV
 - large charm v_2 , small charm R_{AA} → closer to super-opaque, but no secondary charm(!)
- “Perturbative” region may shift to $pT > 5\text{-}10 \text{ GeV}$ due to coalescence and/or soft tails (if very opaque). On the other hand,
 - no quark scaling of v_2 & B/M enhancement from dynamical coalescence approach
 - soft tails could pollute high-pT correlations (must check)
- several other puzzles and open questions:
 - possible thermalization mechanisms (what could make it super-opaque)
 - existence of collective excitations (e.g., conical shocks)
 - what the plasma will be like at the LHC (2007) ...

Nonlinear 6+1D transport eqn: solvable numerically

$$p^\mu \partial_\mu f_i(\vec{x}, \vec{p}, t) = \overbrace{S_i(\vec{x}, \vec{p}, t)}^{\text{source } 2 \rightarrow 2 \text{ (ZPC, GCP, ...)}} + \overbrace{C_i^{el.}[f](\vec{x}, \vec{p}, t)}^{2 \leftrightarrow 3 \text{ (MPC)}} + \overbrace{C_i^{inel.}[f](\vec{x}, \vec{p}, t)} + \dots$$

highly relativistic case → few covariant/causal algorithms: ZPC, MPC, Bjorken- τ , ...
 algorithms → cascade Pang, Zhang, Gyulassy, DM, Vance, Csizmadia, Pratt, Cheng, ...
 → recent attempt - spatial grid Greiner, Xu ...

code repository @ <http://nt3.phys.columbia.edu/OSCAR>

mean free path:

$$\lambda \equiv \frac{1}{\text{cross section} \times \text{density}} \quad \left\{ \begin{array}{l} \lambda = 0 \text{ -- ideal hydrodynamics} \\ \lambda = \infty \text{ -- free streaming} \end{array} \right.$$

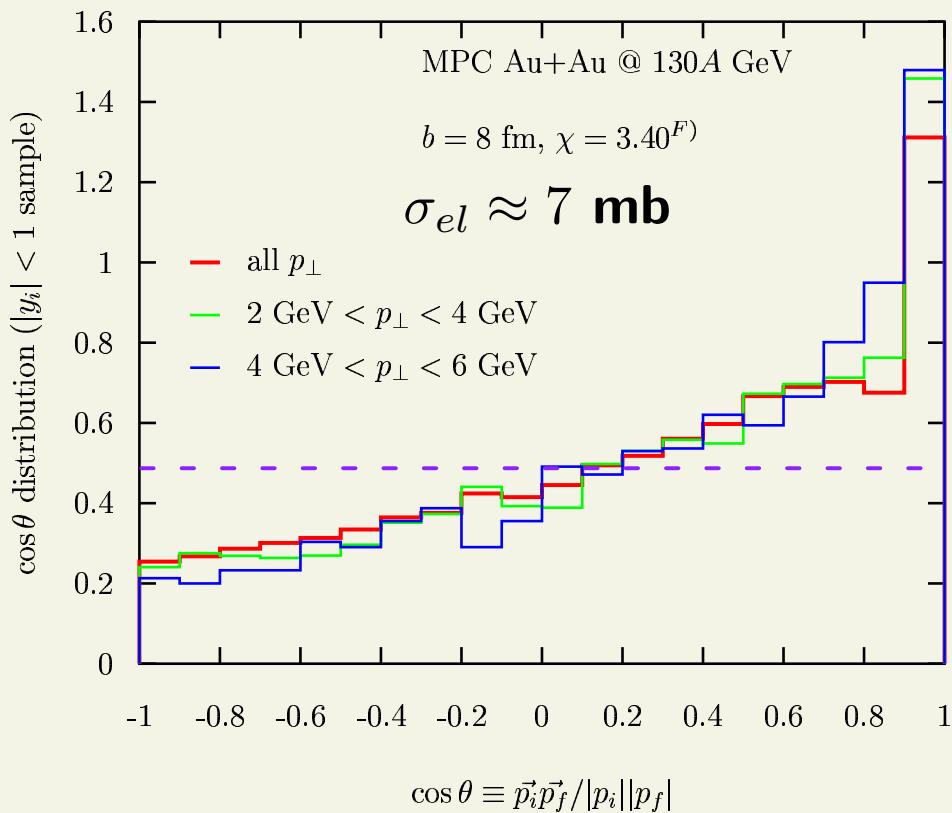
transport opacity: DM & Gyulassy NPA 697 ('02)

$$\chi \equiv \langle n_{coll} \rangle \underbrace{\langle \sin^2 \theta_{CM} \rangle}_{\sigma^{-1} \int d\Omega \frac{d\sigma}{d\Omega} \sin^2 \theta} \sim \# \text{ of collisions} \times \text{deflection weight}$$

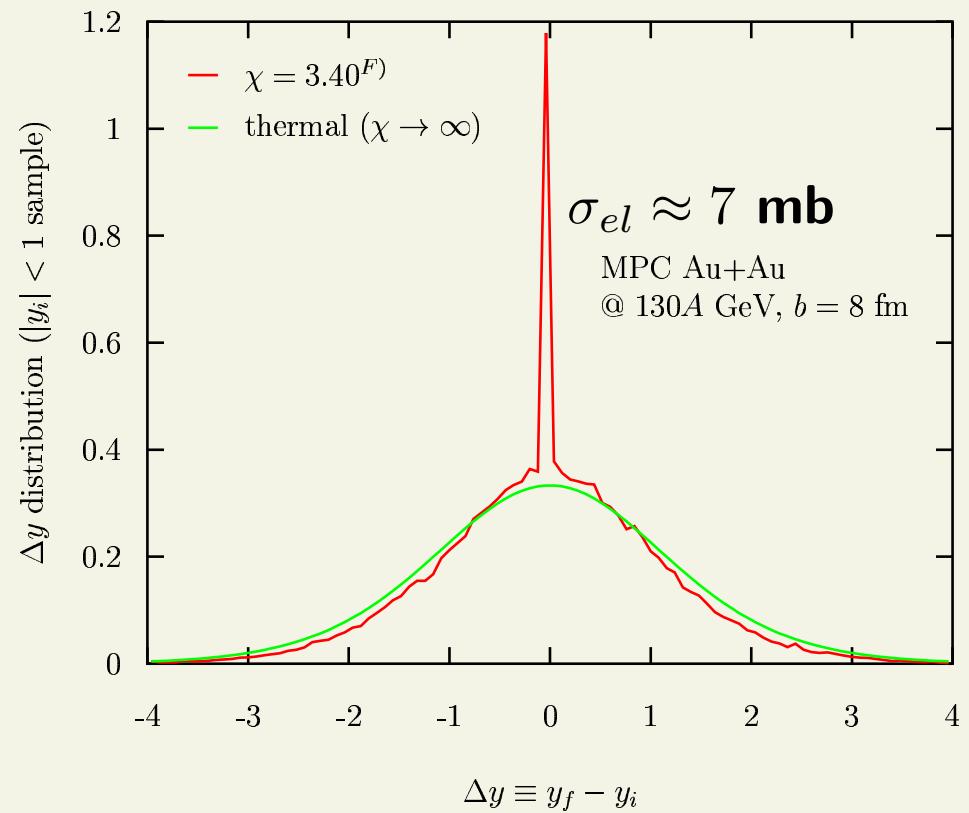
→ $\sigma^{-1} \int d\Omega \frac{d\sigma}{d\Omega} \sin^2 \theta \equiv \sigma_{tr}/\sigma \rightarrow 2/3 \text{ for isotropic}$

Significant randomization

a) deflection angle $\vec{p}_i \angle \vec{p}_f$



b) rapidity shift $y_f - y_i$

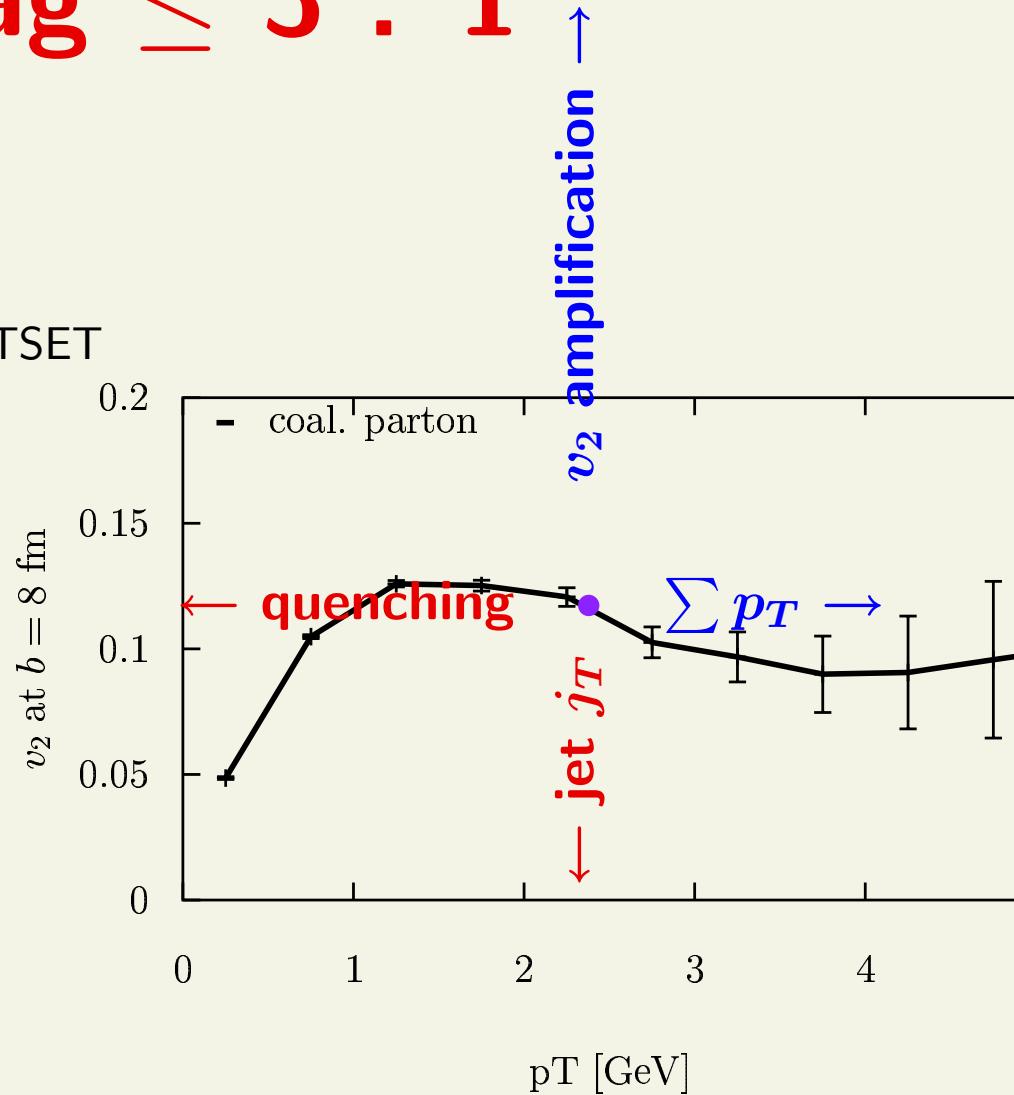
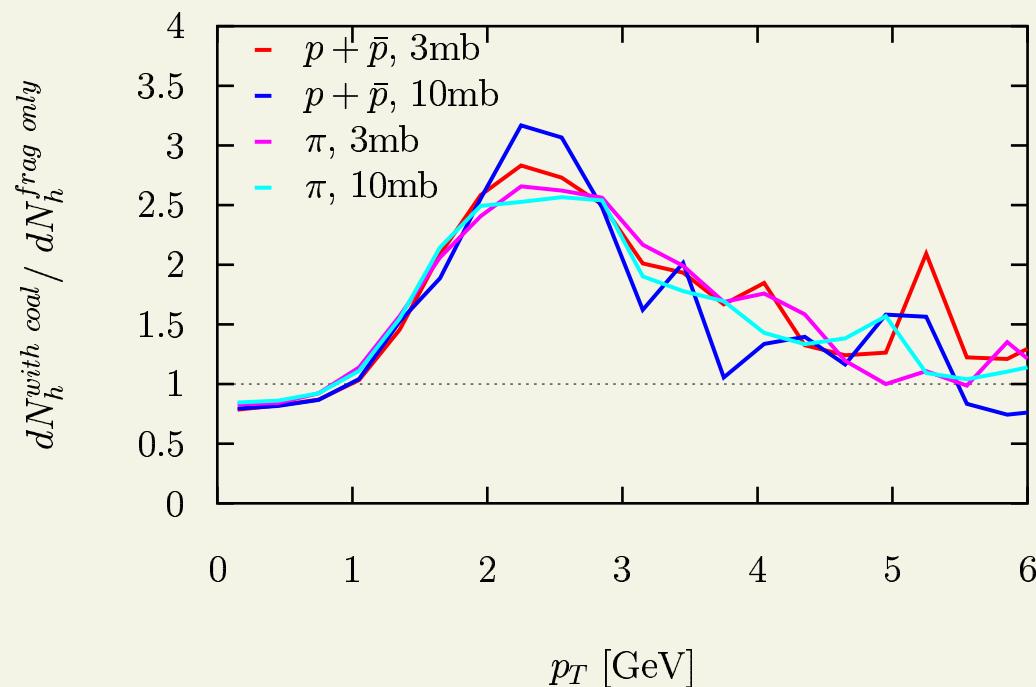


light parton momenta randomize to large degree, already for $\sigma \sim 7 \text{ mb}$ ($\chi \sim 7$)

1. Coal : Frag $\leq 3 : 1$

coal+frag yield / frag only yield

DM ('04): dynamical calculation MPC + coal/JETSET

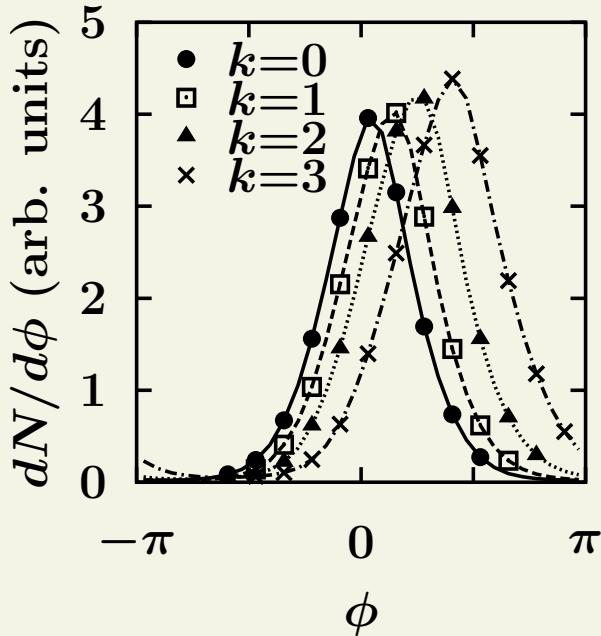
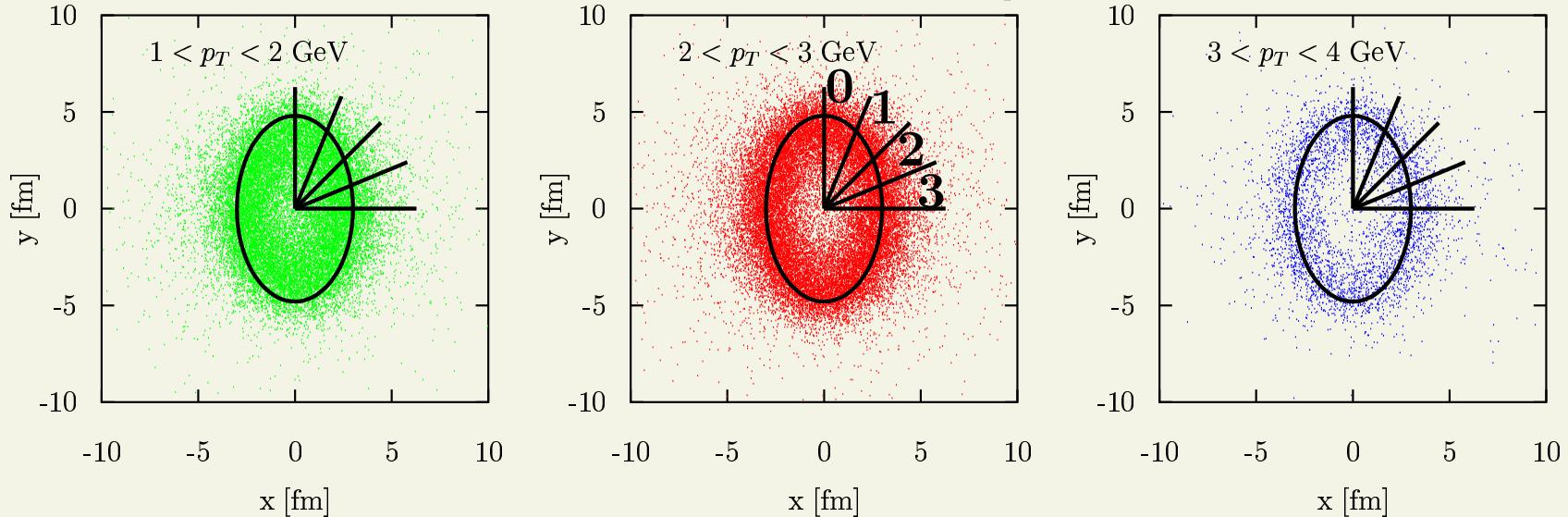


v_2 from $\sim 30\%$ fragmentation contribution does not amplify \rightarrow scaling spoiled

also, about same enhancement for protons and pions $\rightarrow p/\pi$ not enhanced

2. Strong spatial variations

final transverse position distributions ($|y_{rap}| < 2$)



↑ momentum $dN/d\phi$ in each spatial wedge

show surface emission at high p_T $\Rightarrow v_2(x, p_T)$

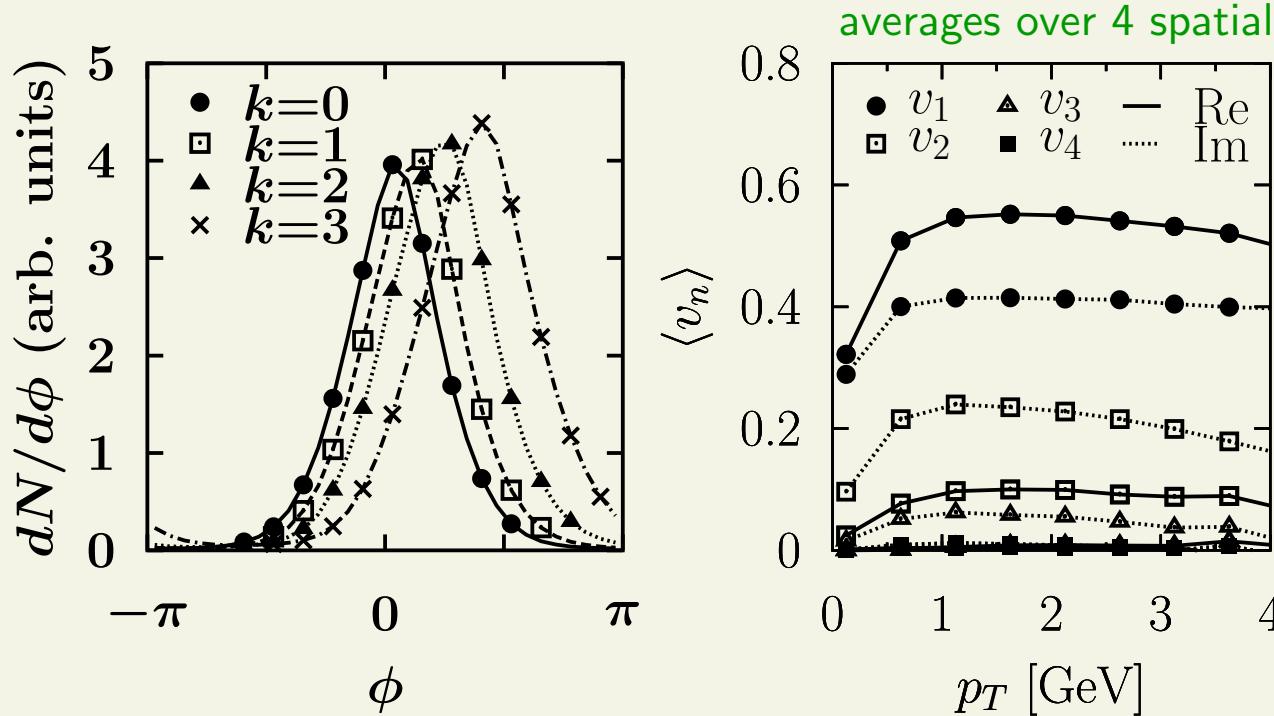
$k = 0$ region: $v_2 < 0$; $k = 3$ region: $v_2 > 0$

expect similar result from hydro

3. Large $|v_n| \sim \mathcal{O}(1)$

DM, nucl-th/0408044

local $\cos(n\phi)$ and $\sin(n\phi)$ anisotropies → use $v_n \equiv \langle \cos(n\phi) + i \sin(n\phi) \rangle$



narrow, almost Gaussian peaks - $dN/d\phi \sim \exp[-(\phi - \phi_0)^2/(2\sigma^2)]$

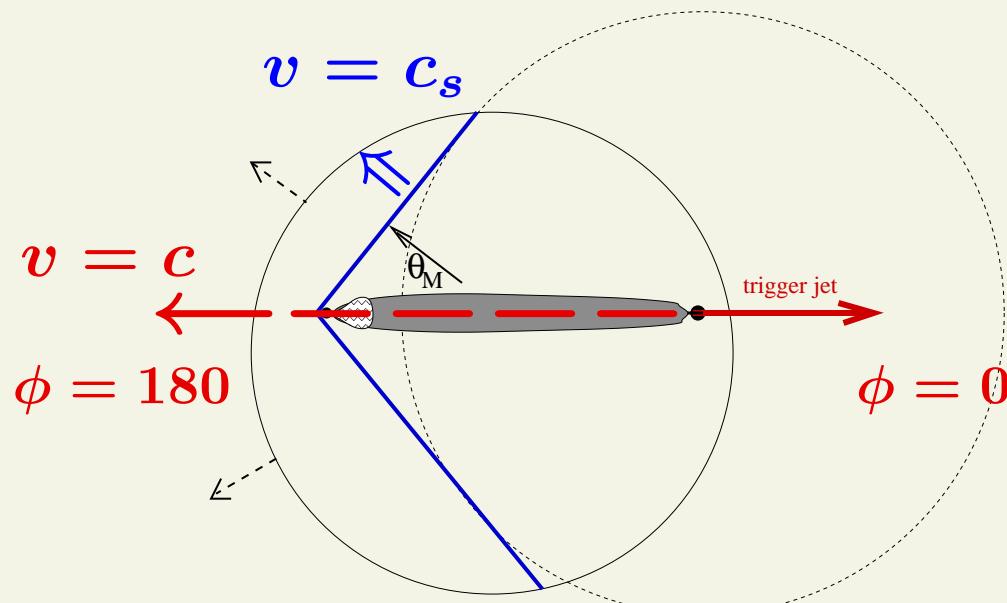
⇒ $|v_n| \sim \mathcal{O}(1)$, $\langle \cos(n\phi) \rangle \equiv \text{Re}v_n = \cos(n\phi_0) \cdot |v_2| \rightarrow \text{varies with } x(!)$

new local scaling: $|v_{k,had}(p_T, x)| \simeq |v_{k,q}(p_T/n_q, x)|^{1/n_q} \neq n_q |v_{k,q}(p_T/n_q, x)|$

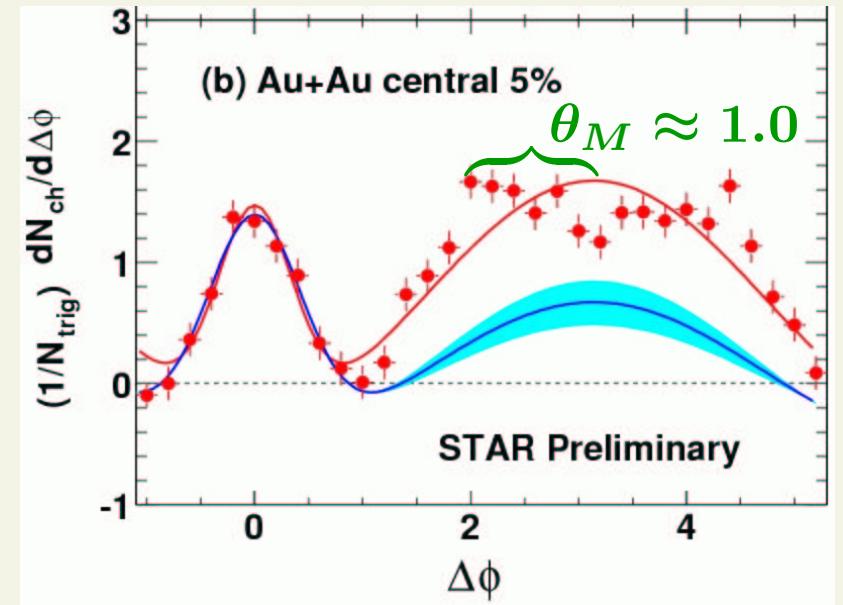
Collective excitations?

Short-wavelength probe could generate collective hydrodynamic response
- exciting, but hotly debated, possibility

“sonic boom” Stöcker '04, Casselderey-Solana et al



azimuthal correlations F. Wang [STAR] '04



$$\text{Mach cone: } \cos \theta_M = c_s/c \quad \Rightarrow \quad c_s^2 \approx 0.25 - 0.3 \cdot c^2 \dots$$

$$\text{ideal parton gas: } c_s^2 = c^2/3$$